

Annotated Bibliography of Urban Wet Weather Flow Literature from 1996 through 2000

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Abstract

This document is a compilation of urban wet-weather flow (WWF) literature reviews for the five years from 1996 through 2000. These reviews were originally published in the annual literature review issues of *Water Environment Research*. Over this five year period of time, many people were involved in preparing these urban wet weather flow reviews, many associated with the EPA's Wet-Weather Flow Research Program. See the acknowledgements section for the complete list of contributors. This paper re-organizes and combines these individual reviews into a single document for easier use. Over this five year period, the field of urban wet weather flow research has expanded dramatically, likely due to increased interest in the US due to the NPDES stormwater permit program, plus increased awareness of the seriousness of urban WWFs throughout the world. About 2500 references are included in this compiled review, indicating the magnitude of interest in this topic. In addition, the number of references for each year has dramatically increased compared to the previous year. Another indication of the increasing interest in urban WWFs is the large number of specialized stormwater conferences that are now scheduled each year, plus the increasing number of nonpoint sessions at large international conferences.

Major proceedings related to WWFs published during 2000 included: (1) 2000 Joint Conference on Water Resources Engineering and Water Resources Planning & Management (ASCE, 2000); (2) WEFTEC 2000, 73rd Annual Conference and Exposition (WEF, 2000); (3) Collection Systems Wet Weather Pollution Control: Looking into Public, Private and Industrial Issues (WEF, 2000); (4) Watershed Management 2000 (WEF, 2000); (5) Applied Modeling of Urban Water Systems, Proceedings of the Conference on Stormwater and Urban Water Systems Modeling (CHI, 2000); and (6) 2000 Annual Meeting and International Conference of the American Institute of Hydrology (AIH, 2000). During 1999, the major published WWF related conference included: (1) National Conference on Retrofit Opportunities for Water Resource Protection in Urban Environments; (2) Comprehensive Stormwater & Aquatic Ecosystem Management, Auckland, New Zealand; (3) the Eighth International Conference on Urban Storm Drainage, Sydney, Australia; (4) Water Environment Federation 72nd Annual Conference and Exposition, New Orleans, LA; (5) American Society of Civil Engineers 26th Annual Conference, Water Resources Planning and Management, Tempe, Arizona; (6) American Water Resources Association 1999 Annual Water Resources Conference – Watershed Management to Protect Declining Species, Seattle, WA; and (7) New Applications in Modeling Urban Water Systems, Guelph, Canada. For 1996, much of the literature cited came from documents covering noteworthy global conferences (Bathala, 1996; Eng. Foundation, 1996; EPA 1996a; Hallam *et al.*, 1996; Int. Water Res. Assoc., 1996; Maxwell *et al.*, 1996; Sieker and Verworm 1996; Soc. Environ. Toxicol. and Chem., 1996; Water Environ. Fed., 1996a, 1996b, and 1996c.). In addition, the U.S. Environmental Protection Agency (EPA) (EPA, 1996b, 1996c, 1996d, and 1996e) published guidance documents which are discussed in more detail in the subsection entitled "Regulatory Policies and Financial Aspects".

The proceedings of several global conferences on urban stormwater management were also published in 1996. James (1996) edited a book overviewing 18 papers dealing with the modeling aspects of urban stormwater. These papers address a variety of topics including the use of the models themselves, data management including GIS, and the interrelationships between BMPs and water quality. The two-volume proceedings of RIVERTECH96 (Maxwell *et al.*, 1996) provided many papers related to urban-stormwater management. The proceedings from a national conference on SSOs provide an excellent information source on SSO problems generally and infiltration/inflow (I/I) problems in particular (EPA, 1996a). The three-volume proceedings of the 7th International Conference on Urban Storm Drainage, held in Hannover, Germany, provide an excellent source of information regarding new developments throughout the world (Sieker and Verworm, 1996).

Introduction

There has been a dramatic shift in the objectives associated with drainage design over the past decades. Burian, et al. (1999) presented a historical development of WWF management as part of the EPA-sponsored research effort on developing designs for the future (Pitt, et al. 1998a and forthcoming CRC book). An extensive annotated bibliography was prepared containing several thousand references tracing the history of drainage design and associated hydraulic and water quality issues. This bibliography (in both text form and in searchable ProCite formats) is available from the student organization AWRAs web page at the Department of Civil Engineering, University of Alabama.

An overview of the evolution of urban drainage, illustrating where the concept of a single design objective was replaced by the sustainability concept, was provided by Marsalek (2000a). The advances highlighted by Marsalek included improved (dynamic) control of urban drainage, source controls, integrated modeling, public and political support,

innovative university training, sustainable funding, adaptive water management, and investment in research and development (Marsalek 2000b). The paper also highlighted the future challenge of involving the public in the planning of drainage systems and protection of urban waters (Marsalek 2000c). Cigana and Couture (2000) advanced a list of key steps required to achieve a global approach to wet weather issues.

The overall challenges of urban drainage design and monitoring were discussed by both Marsalek and Kok (2000) and by Cigana (2000a). Cigana provided a discussion of the pollution resulting from stormwater runoff and combined sewer overflows (CSOs). The paper also reviewed the technologies available to control this pollution. Marsalek and Kok noted that the effectiveness of stormwater BMPs is not fully understood, and advocated future research into the design, operation and maintenance of these pollution control practices. Field (2000) presented an overview of the U.S. Environmental Protection Agency's (EPA's) urban watershed wet-weather flow (WWF) research program. U.S. EPA divided its 1996 research plan into five major areas: characterization and problem assessment, watershed management, toxic substances characterization and control, control technologies, and infrastructure improvement. Since that time, other organizations, notably the Water Environment Research Foundation (WERF), have reviewed WWF research programs and developed associated research needs reports, an effort that EPA endorses.

Sullivan and Field (1999) presented an overview of the Environmental Protection Agency's (EPA's) WWF research program, which was expanded in October 1995 with the establishment of the Urban Watershed Management Branch at Edison, New Jersey. Research priorities for 1999 were presented as well as efforts to collaborate with other government organizations and professional societies. Watershed management research at ORD's National Risk Management Research Laboratory (NRMRL) addressed the following question: what effective watershed management strategies were available and how do communities select the most appropriate subset from these to match specific watershed needs? (Borst and O'Shea, 1999). Heaney et al. (1999) presented the results of a national assessment of research needs in urban WWF management. Three interrelated categories of urban WWF management were discussed: CSO, SSO, and urban stormwater discharges.

Based on the past 30 years of research on urban WWF water quality, impact, modeling, control, and treatment demonstrated results, Field *et al.* (1997a) delineated a framework of future research directions for risk management of urban WWF.

Characterization

General

For California's implementation of industrial stormwater discharge control, Shaver and Duke (2000) characterized Los Angeles industrial facilities as to the types of operations and exposures to rainfall that occur on a site. The results of the survey showed that the majority of sites were impervious, conducted more than one regulated activity, and had a wide range of housekeeping practices and intensities of activity that were exposed to rainfall. The authors questioned whether the general permit should be applied equally to all industrial sites or whether resource allocation should be based on sites where pollutant load reduction potential would be greatest.

The known thermal pollution of Oregon's streams and rivers was reviewed by Bullock and Eimstad (2000), and included a review of sensitive habitats for salmonid species. They presented information on the Oregon Department of Environmental Quality temperature standards for receiving waters, as well as guidance for developing a Temperature Management Plan.

Ball (2000b) reported on the quantities of pollutants that entered the stormwater treatment facility at Centennial Park in Sydney, Australia, and showed that the gross pollutant trap when combined with a wetland or detention pond removed 87% of suspended solids and 50% of the entering phosphorus. Lieb and Carline (2000) investigated the effects of detention pond effluent on a headwater in central Pennsylvania and showed that the macroinvertebrate community immediately downstream of the pond was highly degraded, although recovery was seen farther downstream. Stormwater sediments in Ottawa, Ontario, Canada, were analyzed for their ecotoxic risk by vanLoon et al. (2000). The results indicated that the sediments present significant potential risks to the ecosystems that develop around passive stormwater treatment sites. Jones (2000a) reported on the results of using the US EPA's Rapid Bioassessment Protocol (RBP) in streams affected by stormwater runoff in Fulton County, Georgia. The results of their assessments from 30 stations showed that changes in habitat had a greater effect on the biological communities than did water quality and that control of total suspended solids entering the stream was necessary for habitat protection.

Smullen et al. (1999) compiled stormwater quality data collected from several large sampling programs that have been conducted over the past 20 years. They concluded that it was possible to differentiate stormwater quality based on land use, region of the country, and season. Duke et al. (1999) examined water quality data for separate storm sewer systems during storm event discharges and during dry weather conditions in the San Francisco Bay Area, California. Long-term mean concentrations for many parameters in most streams were higher during storm discharges than during dry-weather flows.

A three-year study on the distributions of concentrations of 14 contaminants in five sources of urban-stormwater-runoff was performed. The log-normal-probability distribution was more accurate in the calculation of pollutant loads than normal-probability distributions (Van Buren *et al.*, 1997).

The runoff on a 95 ha urban catchment in Aalborg, Den. was found to show significant first-flush effects and a strong correlation in concentration between COD and SS and biochemical oxygen demand (BOD) and SS. The study further discussed the most appropriate way to characterize the quality of the outflow comparing average concentration and accumulated event mass methods (Larsen *et al.*, 1997a).

Numerous papers at the 7th International Conference on Urban Storm Drainage held in Hannover, Germany (Sieker and Verworn 1996), presented broad-based stormwater data from throughout the world, including data from Denmark and the Netherlands (Grum *et al.*, 1996), from Poland (Bartkowska and Królikowski, 1996), and from Japan (Uchimura *et al.*, 1996).

Bannerman *et al.* (1996) conducted a study for the USGS in conjunction with the Wisconsin Department of Natural Resources in which water-quality data from four urban stormwater-monitoring projects conducted between 1989 and 1994 were compiled. Concentrations of many of the constituents including Pb; Zn; Cu; Ag (silver); Cd; nine PAHs (polycyclic aromatic hydrocarbons); bis(2-ethylhexyl) phthalate; DDT; atrazine; alachlor, 2,4-D; SS; chlorides; total phosphorus (P); BOD₅; and bacteria were high enough to say that stormwater runoff may be contributing to the degradation of the streams.

Rainfall Monitoring and Urban Hydrology

Schreider et al. (2000) predicted the impact that global warming due to increased carbon dioxide concentrations would have on flood frequencies in the urban areas near Sydney and Canberra, Australia. Their results showed that storms that currently cause the 1 in 100-year flood become the 1 in 44-year event for one basin, and the 1 in 10-year event for another local basin.

Pitt (1999) reports that different drainage design criteria and receiving water use objectives often require the examination of different types of rains for the design of urban drainage systems. These different (and often conflicting) objectives of a stormwater drainage system can be addressed by using distinct portions of the long-term rainfall record. Most of the urban hydrology methods currently used have been successful for large “design” storms, but were inappropriate for use when evaluating many water quality problems.

Urban hydrology

A model (based on dynamic wave equations) for characterizing overland flow on paved surfaces was evaluated by James et al. (2000) and tested successfully using a laboratory-scale rig. Using chloride tracers, Kirchner et al. (2000) showed that many catchments do not have characteristic flushing times. Travel times in the catchments and streams followed an approximate power-law distribution, where contaminants initially were flushed rapidly, but then low-level contamination was delivered to the streams for a long time after the initial flush.

James and Johnson (1999) examined simplified, nondeterministic theories regarding the link between rainfall at the ground surface and the resulting runoff. They showed that linear unit hydrograph theory overlooks the inherent non-linearity in the time dimension of the process. A modified approach, the *initial storage theory* (IST), was therefore proposed and tested in the laboratory. They concluded that the IST was an improvement over the basic unit hydrograph method.

Becker et al. (1999) described the results of detailed field studies investigating lateral flow along different pathways, especially along hillslopes at small catchment scales. Grimmond and Oke (1999) directly measured detailed

evapotranspiration mechanisms for urban areas and found that evapotranspiration varied for different land uses and land covers. Hakonson (1999) studied the effects of the burrowing of pocket gophers and vegetative covers on water runoff amounts and erosion losses and resulted in large decreases in runoff and erosion, while vegetation alone slightly decreased runoff but also greatly decreased erosion. Nagasaka and Nakamura (1999) examined the influences of landuse changes on the hydrologic response and the riparian environment in a northern Japanese area. Temporal changes in a hydrological system and riparian ecosystem were examined with reference to landuse conversion in order to clarify the linkages between the two. The results indicated that the hydrological system has been altered since the 1970s, with increasing flood peaks of 1.5-2.5 times and shortening the time of peak flow appearances by 7 hours. The ecological systems were closely related to and distinctly altered by the changes that have occurred in the local landuse.

During studies in Scotland, Soulsby et al. (1999) found that ^{18}O was a useful tracer to indicate the relative influence of spring snowmelt and summer rainfall on stream waters along with their mean residence times. Preliminary estimates of the various waters' residence times in the catchments were < 0.5 year for near-surface soil water and storm runoff, 2.5 years for shallow groundwater, and >5 years for deeper groundwaters. The effects of frozen soil on snowmelt runoff in Vermont were studied by Stanley and Chalmers (1999). The depth of the soil frost varied greatly during the 15 years of observation, with annual maximum frost depths varying from 70 to 390 mm. The enhancement of runoff due to soil frost was most evident on small plots and during extreme events, such as when rain occurred on frozen, snow-free ground.

In the On-Cheon Stream watershed in Pusan, Korea, the peak discharge of runoff increased and the mean lag time of the study area decreased due to urbanization over the past two decades (Kang et al., 1998). It was not possible to determine a priori what mechanism dominated storm runoff in suburban and forested basins (Burgess et al., 1998). While 12—30% of annual precipitation became runoff in the forest basin, 44—48% became runoff in the suburban basin, emphasizing the need to consider surface flow from all sources in the catchment when evaluating mitigation measures. An evaluation of precipitation records revealed that the majority of storms at most locations are relatively small and produce less precipitation and runoff than is often used in the design of traditional drainage networks (Urbanas, 1998). These storms need to be targeted when attempting to mitigate the effects of urbanization on the receiving waters.

Rainfall errors and flow forecasting

Kawaguchi et al. (1999) presented a case study of short-term rainfall characteristics that showed considerable changes in rainfall intensity during the past 40 years, where the 20-minute rainfall intensity having a 10-year return period increased by 20 mm/hr. This increase in the design storm characteristics has a profound effect on the performance of urban drainage systems. Fo and Crawford (1999) examined rainfall data having a 2 km x 2 km grid resolution over time intervals of 15, 30, 60, and 120 min. to quantify runoff prediction errors in Oklahoma. They found that the test watershed had an average underestimated rainfall error of about 28% which resulted in significant prediction errors when modeling stream flows in the Dry Creek watershed in north-central Oklahoma. Fo et al. (1999) further described new forecast systems using high-resolution rainfall data-sets from the WSR-88D radar system, the Oklahoma Mesonet, and the Oklahoma Local Analysis and Prediction System (OLAPS). They found that because of the lag time between the peak in precipitation and the peak in stream-flow in Dry Creek, the greatest impact upon the accuracy of hydrologic forecasts resulted from improvements in analyzing the precipitation data.

Krejčík et al. (1999) described rainfall data monitoring needs for urban drainage design in the Czech Republic. They verified the need for a high-density network of rain gauges for sewer system design and evaluations, especially when using single-event simulations. The need for high-resolution data was not as great when conducting long-term simulations and when preparing statistical evaluations of the modeling results. Willems et al. (1999) examined intensity/duration/frequency (IDF) relationships for different types of storms and seasons in Belgium. For every re-occurrence time period between 10 min. and 15 days, they identified two separate distributions, one associated with convective thunderstorms and the other with cyclonic/frontal storms.

Nguyen and Nguyen (1999) presented a scaling approach for estimating the distribution of short duration rainfall extremes (e.g., less than 1 hour) from rainfall data having longer durations (e.g., 1 day), using recently developed “scaling” theory. The scaling concept implies that statistical properties of the extreme rainfall processes for different temporal scales were related to each other by a scale-changing operator involving only the scale ratio. Rainfall monitoring with radar. In spite of the highly positive outlook of the obvious benefits, Einfalt and Maul-Kotter (1999) were concerned about the lack of a standard for the use of radar-based precipitation measurements in conjunction with hydrologic models. They described current efforts by the State Environmental Agency in North Rhine-Westphalia, Germany, to investigate the possibilities of developing a standard for radar data use from the German Weather Service for standard hydrological

watershed modeling.

Faure et al. (1999) described some limitations for using radar rainfall data to aid sewage system management. They concluded that weather radar seems an important tool in evaluating the spatial structure of rain and in anticipating very short-term changes in precipitation over an urban area. However, the rainfall variability in space and time restricts the accurate forecasting period. In order to quantify the ability of radar data for forecasting, they examined the forecasting range limits for typical urban catchment areas (1 to 180 km²) in Nancy, France. They found that the limits varied greatly according to the rain conditions, leading them to propose a sewage system management strategy based on predefined management scenarios and real time identification of the type of the rain event. Koishikawa et al. (1999) also examined the application of rainfall radar information for use with operational support systems used for urban drainage facilities. They found that in order to be effective, the radar rainfall data must be collected accurately and with high resolution in both time and space. They demonstrated increases in the accuracies of runoff simulation modeling when adequate radar rainfall data were used. Vivekanandan et al. (1999) studied the influence of terrain on rainfall estimates from radar for a severe storm near Denver, Colorado. Estimates of rain intensities in areas having low or high beam-blockage were compared. They found that specific propagation phase-based quantitative precipitation estimates tend to be less influenced by terrain than reflectivity-based precipitation estimates, as they had hypothesized.

One of the most unappreciated tasks associated with stormwater characterization is an understanding of urban-rainfall patterns and rainfall-monitoring requirements. The Danish Meteorological Institute (Mikkelsen *et al.*, 1996a and 1996b) has established a nationwide-raingauge network for monitoring short- and intense-rain events. This was of special interest in designing stormwater-drainage systems. It was found that a large geographical variation in rainfall cannot be described by typical topographic or other standard factors. Therefore the way that rainfall data are being used by engineers for design and analysis is being revised. Arnbjerg-Nielsen and Harremoës (1996) coupled a stochastic time-series model with a model for the geographical variation of extreme point rainfall in order to make inference about extreme rainfalls at ungauged locations. The use of the U.S. NEXRAD-radar system for estimating point rainfalls was discussed by Seliga and Chen (1996). This information should be very useful, especially within an urban environment.

Desa and Niemczynowicz (1996) studied short-term- and long-term-rainfall patterns in Malaysia. These were the first rainfall data having very small-time and -space resolution in the humid tropics region.

The City of Philadelphia's modernized raingauge network provides the Water Department with a method of preplanning for events based on intensity and duration and the ability to determine publicly owned treatment works (POTW) effects on multiple events (Day and Nicolo, 1996). It provides information, which can be used for calibrating models, to aid in improving general effluent quality and plant operations.

Legg *et al.* (1996) investigated the rainfall-runoff relationship for 20 residential lawns in Madison, WI using a rainfall simulator, in order to identify the significant factors affecting infiltration in disturbed urban soils. All lawns were characterized as having silt-loam soils. The runoff coefficients for lawns younger than three years were significantly greater than for older lawns. Changes in rain intensity had little effect on runoff volumes, with total rainfall depth having the most significant effect. The effect of antecedent-soil moisture on infiltration was questioned, requiring more study.

Urban Snowmelt

Thorolfsson and Brandt (1996) studied urban storm runoff during summer and winter in Norway from 1988 through 1994. It was found that snowmelt runoff is much greater in volume than typically considered in drainage designs, resulting in much more winter flooding and CSOs than during the summer. An urban storm-runoff model that considers snowmelt and rainfall was produced but it was concluded that there is still a notable lack of experience about urban storm runoff during the winter season.

Saxton *et al.* (1996) reported the results of a study conducted to quantify the pollutant characteristics of snow versus snowmelt runoff at Eielson Air Force Base, AK. The sampling results showed that snow is, in general, more contaminated than snowmelt runoff and that snowmelt runoff appears to be representative of what reaches surface water.

Sansalone (1996) investigated the forms of heavy metals in stormwater and snowmelt. It was found that zinc (Zn), cadmium (Cd), and copper (Cu) were mainly dissolved in stormwater, while only Cd was mainly dissolved in snowmelt. Lead (Pb) was associated with the finer particulate fractions in both stormwater and snowmelt. The dissolved fraction of the metals should be immobilized by sorption, while the particulate bound metals should be immobilized by filtration in a

partial exfiltration trench.

Stormwater Quality

EMCs were analyzed by Behera et al. (2000) for areas of Toronto, Canada, that had both separate and combined sewer systems, and noted that the data followed the gamma and exponential probability distributions, in addition to the log-normal probability distribution. Lee and Bang (2000) investigated the relationship between pollutant loadings and runoff flows, especially the first flush in the urban areas of Taejon and Chongju, Korea. They found that the pollutant concentration peak occurred earlier than the flowrate peak in areas smaller than 100 ha where impervious area was more than 80%. However, in areas more than 100 ha with impervious area of less than 50%, the pollutant concentration peak followed the flow rate peak, with this second order occurring more frequently in watersheds with combined sewer systems. Mattson et al. (2000) investigated the event mean concentrations of a range of pollutants in urban stormwater runoff that entered the Severn Sound. In samples from the beach areas, they found *E. coli* concentrations exceeding 600 organisms/100 mL when rain events were greater than 20 mm. The model of the stormwater entering the Sound estimated a phosphorus loading of 1083 kg/yr.

The impact of experimental watershed acidification on xylem cation chemistry was evaluated in eight species at two sites in West Virginia (Clover Run and Fernow) and one site in Maine, BBWM. Experimental watershed acidification or N saturation using applications of $(\text{NH}_4)_2\text{SO}_4$ equivalent to twice the normal annual wet plus dry N and S deposition caused base cation mobilization followed by depletion that was detectable in sapwood xylem after about 8 yr. of treatment (Dewalle et al., 1999).

A study of stormwater-runoff quality from two adjacent urban watersheds in Singapore used continuous recording of rainfall and stream flow within the basins and systematic sampling of stormwater runoff during rainfall events. Correlations of EMC and SS and chemical oxygen demand (COD) loads to both antecedent-dry-weather period and rainfall characteristics were conducted (Chui, 1997). Muller *et al.* (1997) conducted a five-year study of the seasonal input variation and the distribution and residence time of herbicides in three Swiss lakes. The compounds investigated showed a conservative behavior in the water column of the lakes with triazine herbicides and the metabolites occurring in the epilimnion during or right after the application period and the annual input of atrazine depending on the rainfall during the application period. A three-year study (Vanburen *et al.*, 1997) of parking-lot discharges into an on-stream pond concluded that log-normal was the better distribution for parking-lot runoff and creek baseflow while less suitable for creek event flow and pond baseflow. A normal distribution applied for soluble constituents (total dissolved solids [TDS], chlorides, sulphate, COD) and/or event outflow from the pond. Munn and Gruber (1997) studied the relationship between land use and organochlorine compounds in streambed sediment and fish in the Central Columbia Plateau in eastern Washington and Idaho and reported that most organochlorine compounds were still present in the environment.

A sampling program in North Carolina collected the first flush at 20 different sites covering ten different industrial groups (Line *et al.*, 1997). Zn and Cu were the most common metals found while other contaminants included volatile and semivolatile organics, pesticides, and conventional pollutants, especially, nutrients and solids, which had high concentrations when a significant amount of biological waste or exposed soil was present. Muscara *et al.* (1997) reported typical pollutants, i.e., Fe, Zn, nickel (Ni), nitrate as nitrogen ($\text{NO}_3\text{-N}$), and nitrite as nitrogen ($\text{NO}_2\text{-N}$), leaving a highway construction site near Houston, Tex.

Thomson *et al.* (1997a) examined the relationships between surrogate parameters (i.e., SS, TDS, total volatile solids, and TOC) and other constituents of interest (e.g., metals, ionic species, and nutrients) by using the Minnesota highway stormwater quality database for regression analysis. The findings indicated that the metal and nutrient constituent relationships were limited to urban sites with similar environmental conditions. Further, statistical model analysis of monitoring results (Thomson *et al.*, 1997b) concluded that approximately 15 — 20 samples are required to provide reasonable estimates of the mean concentrations of runoff events for SS, TDS, TOC, and Zn.

Litter

Armitage and Rooseboom (2000a) demonstrated that large quantities of litter are being transported in South Africa in urban stormwater runoff, and that the amount of litter produced was related to land use, vegetation, level of street cleaning and type of rainfall. The benefits of litter reduction were documented using their work in Australia and New Zealand, and design equations for sizing litter traps were proposed (Armitage and Rooseboom 2000b). Newman et al. (2000a) characterized the floatables found in urban stormwater runoff. The results of this study were to be used to develop transport models of the movement of and controls for these floatables.

The principal source of litter on the Bristol Channel of the United Kingdom was postulated as riverine derived from sanitary-wastewater debris originating from CSO (Williams and Simmons, 1997a). River bank clearances provided valuable information on litter accumulation and movement showing a distinctive correlation between flood events and litter movement. Some litter types have an increased input during flood events, e.g., sanitary-wastewater-derived material from combined sewer outfalls, whereas accumulation of other litter types could be due to their distribution throughout the catchment (Williams and Simmons, 1997b).

Nutrients

Ball and Abustan (2000) investigated the phosphorus export from an urban catchment in Sydney, New South Wales, Australia, and derived a relationship between inorganic suspended solids and particulate phosphorus for this catchment. These results were to be used to predict the performance of detention ponds and/or wetlands for treating this runoff.

Sixteen largely agricultural watersheds in the upper portion of the North Bosque River of central Texas were reported by McFarland and Hauck (1999). The proportion of total P (TP) in runoff represented by soluble reactive P (SRP) also increased as the percent of dairy waste application fields above a sampling site increased.

Fluxes of total phosphorus (P), total phosphate, and total organic P from seven small watersheds on the Atlantic Coastal Plain of Maryland for up to 25 years were reported by Correll et al. (1999), indicating cropland watershed's P flux were much higher than forested watershed and increased significantly with precipitation. The Bear Brook Watershed in Maine (BBWM) was the sight of a paired watershed study in which the West Bear (WB) catchment was being artificially acidified with $1,800 \text{ eq ha}^{-1} \text{ y}^{-1}$ of $(\text{NH}_4)_2\text{SO}_4$ resulting in changes in the soil and stream chemistry, while the East Bear (EB) serves as the control (Norton et al., 1999). P chemistry in streams was evaluated at the pair watershed study at the BBWM, indicating the export of Al and P was greater from the treated watershed because the induced acidification was translocating more Al from soils to the streams and the export of P was related to acid-soluble Al particulate material (Roy et al., 1999). One hundred and sixty-two rainfall-induced soil erosion tests were conducted to assist in predicting soil loss and subsequent increase in total suspended solids, indicating soil loss was dependent upon rainfall intensity, and the soil's shear and compressive strength (Liu et al., 1999). After six years of monitoring flow and water quality Jaynes et al. (1999) conclude nitrate appears to be the primary agriculturally related pollutant of concern in Walnut Creek, California thus management practices designed to reduce NO_3 leaching from fields and increase removal within the watershed/stream system should receive primary consideration.

Microorganisms

As part of a modeling exercise for predicting removal of beach closure restrictions after a storm event, Jin et al. (2000) characterized the movement of indicator organisms (*E. coli*, *enterococci*, and fecal coliforms) from stormwater outfalls in Lake Ponchartrain to Lincoln Beach in New Orleans. They found that, as expected, a rapid decrease in organism concentration occurred near the outfall and that two or three days after pumping, indicator organism concentrations at Lincoln Beach were below the health standards for swimming. Their data also showed that *E. coli* was a better indicator organism for fresh water environments, while *enterococci* was more suited for use in marine or brackish environments.

Francy et al. (2000) related potential sources of microorganisms (total coliforms, *Escheria coli*, and *Clostridium perfringens*) to receiving water quality. In general, fewer organisms were found in the groundwater. Land use was found to have the greatest influence on bacterial indicators in stream water, while presence of septic systems and well depth had the greatest influence on the bacteria concentration in groundwater. Skerrett and Holland (2000) found that *Cryptosporidium* oocyst occurrence in Dublin, Ireland, area waters increased after a heavy rainfall, likely due to increased the runoff volume into the receiving water. Their results also showed that *Cryptosporidium* oocysts were widely dispersed in the Dublin-area aquatic environment.

Waters adjacent to the County of Los Angeles, California receive untreated runoff from a series of storm drains year round, in which persons swim there were exposed to these untreated waters. Measures of exposure included distance from the storm drain, selected bacterial indicators (total and fecal coliforms, enterococci, and *Escherichia coli*), and a direct measure of enteric viruses. It was found higher risks of a broad range of symptoms, including both upper respiratory and gastrointestinal, for subjects swimming (a) closer to storm drains, (b) in water with high levels of single bacterial indicators and a low ratio of total to fecal coliforms, and (c) in water where enteric viruses were detected (Haile et al., 1999). Particulate fluxes of aliphatic and aromatic hydrocarbons were measured with a sediment trap moored at 80 m depth offshore of Monaco (200 m water column) during an 18-month period (Raoux et al., 1999). Timperley (1999)

described the concepts of chemical bioavailability and its relevance to urban stormwaters and streams.

Water samples were collected from four locations within the Munnell Run Watershed in Mercer County, Pennsylvania, and analyzed for fecal coliforms by MPN and enteric phages by plaque assay using *Salmonella typhimurium* WG 49 and *Bacteroides fragilis* HSP 40 as hosts. The presence of host specific phages indicate the existence of septic discharges in the watershed, but both fecal coliforms and enteric viruses persist in stream systems, especially during the summer months (Brenner et al., 1999).

Ferguson et al. (1998) found 50% of 34 first-flush samples taken from two major watersheds tested positive for *giardia* cysts and *cryptosporidium* oocytes. This information will be used to review the current source water monitoring program conducted by the Metropolitan Water District of South. Calif. and to assist in the implementation of watershed management strategies to control protozoa in source waters. A literature review (Bagley et al., 1998) revealed that the cysts of *giardia lamblia* and *cryptosporidium* species oocysts are commonly detected over a wide range of concentrations in a wide variety of aquatic systems.

In a southern California study, eight of 12 plants were positive for *salmonella* at the chlorination/dechlorination site and effluents from 11 of 12 plants were positive for *salmonella* when sampled downstream of the chlorination/dechlorination site before merging with the receiving stream (Kinde et al., 1997). Two of the three control sites, i.e., an urban-stormwater-runoff and a raw-potable-water reservoir, were also positive for *salmonella*. Fecal coliform (FC) and fecal streptococci densities were detected at 12 sites in the Buffalo River watershed during 1992-1993 with the highest levels of indicator bacteria in the water column coinciding with rainfall events; however three sites closest to the Buffalo River violated New York State water quality standards of FC levels in 79% of all samples. SS were strongly correlated with FC ($r = 0.86$) in the upper watershed during the summer months when flow velocities were greatest and solids may play an important role in transporting bacteria into the Buffalo River (Pettibone and Irvine, 1997). Urban stormwater runoff from various large urban developments in South Africa were investigated to establish the extent of fecal pollution (Jagals, 1997). The level of sanitation ranged from pit and bucket latrines to full-waterborne-sewerage systems. Stormwater runoff from developing urban settlements, as well as developed urban structures, constituted a major source of pollution for a downstream river catchment used as a source of water for human consumption and recreation.

Toxicity

Parker et al. (2000) analyzed the sediment found in urban stormwater runoff in the Phoenix, Arizona, metropolitan area. They found that the inorganic content of the sediments was similar to that in soils that were not impacted by urban runoff. The metals concentrations (Cd, Cu, Pb, and Zn) were higher, but below levels that would recommend remediation. Arsenic concentrations were above recommended levels; however, this contribution likely was geologic not anthropogenic. Chlordane, DDT (and DDE and DDD), dieldrin, toxaphene, and PCBs were found in the sediments at all sampling locations. Sediment toxicity was seen, but could not be explained based on their chemical results. Vollertsen and Hvitved-Jacobsen (2000) investigated the resuspension of sewer solids in combined sewers. They found that sewer solids that were undisturbed for up to two weeks were more easily resuspended and their oxygen uptake rate was significantly greater than fresh solids, indicating that the flushing of these solids into receiving waters may cause oxygen depletion problems.

Love and Woolley (1999) found that stormwater was alarmingly more toxic than treated sewage. The Concord project, funded by EPA, examined the possibility of needed treatment for reuse of residential area stormwater before source area. Runoff from sawmills in British Columbia was monitored for toxicity by Bailey et al. (1999) and found that 42 of the 58 samples were toxic to juvenile rainbow trout. Divalent cations, especially zinc, were the most common source of the toxicity. Tannins and lignins, associated with bulk log handling, were responsible for the remaining toxicity.

A stormwater toxicity study for Santa Monica Bay, Calif. included analysis of surface water and sediment samples following four significantly-sized storms. Toxicity was present in water samples offshore and was proportional to the concentration of runoff in the plume and changes in sediment characteristics, such as grain size and total organic carbon (TOC), were also evident (Bay et al., 1998).

Heavy metals

Williamson and Morrissey (2000) modeled the build-up of heavy metals (Pb, Zn, and Cu) in urban estuaries due to stormwater contamination, with the model being based upon the behavior of the metals in runoff and during transport in the estuarine system.

Urban stormwater runoff was targeted by Neto et al. (2000) as a potential source for the elevated metals (Pb, Zn, Ni, Cu and Cr) concentrations found in Jurujuba Sound in Southeast Brazil. Investigation of sediment cores indicated that the increase in sediment metals concentration occurred at approximately the time that rapid urbanization began in the watershed.

Barbosa and Hvitved-Jacobsen (1999) examined heavy metals in highway runoff in Portugal. Concentrations of Cd and Cr were usually lower than the detection limit (1 µg/L), copper levels were between 1 and 54 µg/L, lead from 1 to 200 µg/L, and zinc from 50 to 1460 µg/L. A lowering of the pH value increased the desorption of previously retained Zn, Cu and Pb from the soil lining the infiltration pond used to treat this water.

Barry et al. (1999) identified salinity effects on the partitioning of heavy metals in the stormwater canals entering Port Jackson (Sydney), Australia. Cu, Pb, and Zn was found increasingly in dissolved phases as the salinity increased in the lower sections of the canals. During high flows, most of the metals seemed to be rapidly exported from the estuary as a discrete surface layer, while low flows contributed most of the metals to the estuary. Birch (1999) also studied the Port Jackson estuary sediments. Historical industrial activity was responsible for much of the contaminated sediments, but atmospheric contributions were also likely important. Stormwater from small catchments, along with sewer overflows, had no observable effects on the distribution of heavy metals in surficial sediments.

Grout et al. (1999) studied the colloidal phases in urban stormwater runoff entering Brays Bayou (Houston, Texas). Colloids in the filtrate after 0.45 µm filtering and further separation by ultracentrifuging, accounted for 79% of the Al, 85% of the Fe, 52% of the Cr, 43% of the Mn, and 29% of the Zn present in the filtrates. Changes in the colloidal composition were caused by changes in colloidal morphologies, varying from organic aggregates to diffuse gel-like structures rich in Si, Al, and Fe. Colloids were mostly composed of silica during periods of dry weather flow and at the maximum of the stormwater flow, while carbon dominated the colloidal fraction at the beginning and declining stages of the storm events. Garnaud et al. (1999) examined the geochemical speciation of particulate metals using sequential extraction procedures for different runoff sources in Paris, France. They found that most metals were bound to acid soluble particulates in the runoff but that copper was almost entirely bound to oxidizable and residual fractions.

Datta and Subramanian (1998) report that despite a very dense population in its watershed, the lower Ganges-Brahmaputra-Meghna drainage basin remains relatively-unperturbed alluvial basin with regards to heavy metal pollution, due in part to a very high rate of sediment deposition.

A study by Sansalone and Buchberger (1997) analyzed stormwater runoff at five sites on a heavily traveled roadway in Cincinnati, Ohio. They found that the event-mean concentrations (EMC) of Zn, cadmium (Cd), and copper (Cu) exceeded surface-water-quality-discharge standards. Further, it was noted that Zn, Cd, and Cu are mainly in the dissolved form while other metals, i.e., lead (Pb), Fe, and aluminum (Al) are mainly bound to particles.

Analytical techniques were used to determine the speciation of Cu and Ni in point and non-point source (NPS) discharges and found that the existence of a strong metal-complexing ligand in wastewater effluent, and to a lesser degree, surface runoff must be accounted for when evaluating metal treatability (Sedlak *et al.*, 1997).

Organic toxicants

In the central Paris district of “Le Marais,” Gonzalez et al. (2000) found PAHs primarily in the particulate phase in all catchments, with the median concentration in combined sewer overflows of 204 ng/L. Phenanthrene, anthracene, fluoranthene and pyrene were the most observed compounds. The results indicated that atmospheric deposition was an important source of PAHs in urban stormwater runoff. Ngabe et al. (2000) analyzed urban stormwater runoff in coastal South Carolina for PAH content. The authors found the highest concentrations (5590 ng/L) of PAHs in runoff from Columbia, a major metropolitan area, and lower concentrations (282 ng/L) from the small town of Murrells Inlet. The PAH profiles in the runoff from the two urban areas were similar to those found in atmospheric deposition and unlike those in used crankcase oil. However, the aliphatic fraction of the organics in Columbia’s runoff were more similar to used crankcase oil than to urban aerosols.

Shinya et al. (2000) investigated the concentrations of metals and PAHs in the runoff from four urban-highway rainfall drains. The results showed a first flush of both metals and PAHs. Most of the metals were tied up with the particulate matter, as were the higher molecular weight PAHs. Phenanthrene, fluoranthene, and pyrene comprised about 50% of the

quantified PAH constituents in each sample. Smith et al. (2000a) analyzed for PAHs in stormwater runoff from four locations in an urban area: a gas station, a highway off-ramp, and a low- and a high-traffic volume parking lot. The gas station site produced the highest total PAH loading (2.24 g/yr/m²), followed by the high-traffic-volume parking lot (0.0556 g/yr/m²), the highway off-ramp (0.052 g/yr/m²), and the low-traffic-volume parking lot (0.0323 g/yr/m²). PAH concentrations were usually highest during the 'first flush' of storm-water runoff and tapered off rapidly as time progressed. The concentrations and characteristics of organic carbon (as DOC) in surface waters in Arizona were studied by Westerhoff and Anning (2000). Fluorescence measurements indicated that DOC in desert streams was from autochthonous sources; however, DOC in unregulated upland rivers and desert streams shifted from autochthonous to allochthonous sources during runoff events. The urban water system affected temporal variability in DOC concentration and composition.

Analysis of patterns in pesticide use revealed that concentrations of herbicides and insecticides in agricultural streams, and in most rivers in agricultural regions, were highest in those areas of the nation with the greatest agricultural use. More than 95% of the samples collected from streams and almost 50% of samples collected from wells contained at least one pesticide (Gilliom et al., 1999).

Fisher et al. (1999) found trace concentrations of dioxins and furans in urban runoff entering Santa Monica Bay, California over a 1-year sampling period. Concentrations of polychlorinated dioxin and polychlorinated furan peaked during storms. The congener and isomer profiles resembled profiles found in lake sediments and rainwater more than they resembled profiles found in urban sources such as dioxins from incinerators or dioxins in contaminated commercial products. Runoff from open land use areas had lower concentrations than runoff from developed land uses. Wenning et al. (1999) studied polychlorinated dibenzo-p-dioxins/dibenzofurans (PCDD/Fs) in stormwater collected from 15 outfalls entering San Francisco Bay, California. Monitoring locations were located both adjacent to and distant from petroleum refineries and included mixed urban/commercial/residential land uses. Few significant differences were found between stormwater in areas adjacent to vs. further from the petroleum refineries. They found that nonindustrialized urban locations may represent important sources of PCDD/Fs to San Francisco Bay.

The environmental fate, chemistry, and toxicity of aircraft deicing compounds (mainly ethylene, propylene, and diethylene glycol) commonly used in Canada was investigated by Kent et al. (1999). Glycols were miscible in water and they were highly mobile. Aerobic biodegradation was the most important environmental fate process affecting glycols in waters and soils. Glycols have relatively low aquatic toxicity, with algae being more sensitive than vertebrates or invertebrates, but the aircraft deicing/anti-icing fluids were more toxic than pure glycols.

Seasonal changes of the herbicides (diuron and simazine) in urban runoff were examined by Revitt et al. (1999). The herbicide concentrations were higher in storm events, with maximum levels of diuron at 238 µg/L and simazine at 2.2 µg/L recorded. The very high diuron level was during a storm event, which closely followed application of the herbicide. During this event, more than 45% of the applied diuron was lost to runoff. Qian and Anderson (1999) examined five commonly used herbicides and three pesticides in small streams in the Willamette River Basin, Oregon. Of the variables examined, landuse was the most important for all but one (simazine) of the eight pesticides studied, followed by geographic location, intensity of agriculture activities in the watershed, and the size of the watershed. There were significant differences in the variabilities of the stream concentrations for the urban and agriculture sites. While all 16 nonurban watersheds had significantly higher variations than the urban sites, the same was not necessarily true for the mean concentrations.

Several stormwater-runoff samples were accurately evaluated for oil and grease with an alternative analysis method using octadecyl siloxane (¹⁸C) solid-phase-extraction columns. The amount of the solvent was reduced and more reproducible results were obtained using this alternative method (Lau and Stenstrom, 1997).

Crunkilton and Devita (1997) investigated the concentrations of freely dissolved polycyclic aromatic hydrocarbons (PAH) in an urban stream at high flow and baseflow by an equilibrium partitioning model (EPM) and by use of lipid-filled semipermeable membrane devices (SPMD). The results, compared to direct measurements made on bulk (unfiltered) water samples, indicated that concentrations of freely dissolved PAH and total PAH at high flow are about 20 times greater than at baseflow. In another study, Kucklick *et al.* (1997) investigated the contamination of PAH in surface sediment of Winyah Bay, Charleston Harbor and the North Edisto River estuary in South Carolina. Concentrations of total PAH (i.e., analyzed for 24 PAH, two to six rings), were extremely variable; however, this observed variability was not explained by total organic carbon (TOC) or grain size, indicating that other factors were more important. Loganathan

et al. (1997) evaluated sources of polychlorinated biphenols (PCB) in CSO to the Buffalo River, N.Y. by analyzing combined and sanitary wastewater, atmospheric wet and dry deposition, and street dust samples from the Babcock Street sewer district. PCB congener composition suggested that the local contaminated street dusts are one of the potential sources of PCB in CSO and to the Buffalo River.

Particle size/settling

Hijioka *et al.* (2000) investigated the behavior of suspended solids in runoff from a 67-ha urban watershed by looking at the behavior of two separate fractions (fine – less than 45 μm ; coarse – greater than 45 μm). They found that the two fractions behaved similarly; however, the pollutant loadings were different with the coarse fraction needing a more intense storm to generate runoff containing that fraction.

The composition and morphology of colloidal materials entering an urban waterway (Brays Bayou, Houston, Texas) during a storm event was investigated. Analyses of organic carbon, Si, Al, Fe, Cr, Cu, Mn, Zn, Ca, Mg, and Ca were performed on the fraction of materials passing through a 0.45 μm filter. This fraction, traditionally defined as "dissolved", was further fractionated by ultra-centrifugation into colloidal and dissolved fractions (Grout *et al.*, 1999).

Lloyd and Wond (1999) presented examples of particulate size fraction distributions for road and highway runoff collected in Australia and compared the information with United States and European samples. They found that the particle size distribution of suspended solids in stormwater runoff from roads and highways in Australia were relatively finely graded. Sansalone and Hird (1999), in contrast, found that the particle sizes of stormwater particulates investigated at a freeway site in Cincinnati, Ohio were much larger than typically found elsewhere. In their samples, particles several hundred μm in size were common. They stressed the need to carefully collect stormwater samples for particle size analyses considering the difficulty of representing large particles in samples collected with automatic samplers. Pitt *et al.* (1999), during pilot-scale testing of a critical-source-area-treatment device, monitored particle size characteristics both in the influent and effluent. The parking lot stormwater had median particle sizes ranging from 3 to 15 μm . They also monitored particle sizes from 75 source areas in the Birmingham, Alabama, area as part of treatability tests during an earlier phase of this research and found similar small-sized particles. Corsi *et al.* (1999) measured stormwater particle sizes as part of a treatment system evaluation at a public works yard in Milwaukee, Wisconsin, and found median particle sizes in the influent of about 18 μm .

Andral *et al.* (1999) analyzed particle sizes and particle settling velocities in stormwater samples collected from eight storm events from the A9 motorway in the Kerault Region of France. They concluded that to effectively treat runoff, particles smaller than 50 μm in diameter (which represented approximately three-quarters of the particulates analyzed, by weight) must be captured. The median particle size for their samples averaged about 15 μm . Settling velocities of these particulates were also studied. The median settling velocities of the particulates smaller than 50 μm ranged from 2.5 to 3.3 m/h, while the larger particles between 50 to 100 μm in diameter had median settling velocities ranging from 5.7 to 13 m/h. Krishnappan *et al.* (1999) examined particle size distributions of suspended solids in a wet detention pond. They used a submersible laser particle size analyzer that enabled them to examine the particulate characteristics without disturbance by sampling. They found that the suspended solids were mostly composed of flocs, with maximum sizes ranging from 30 (winter) to 212 μm (summer). They concluded that flocs in the size range from 5 to 15 μm would settle faster than both smaller primary particles of higher density, and somewhat larger flocs of lower density. The larger flocs were also found to be susceptible to break up by turbulence.

Organic matter in sediments from pipes and silt traps in combined sewers was divided into fractions with different settling velocities. The largest fraction of organic material was found in the faster settling material, however the faster settling material had a slower biodegradability than the slower settling fraction (Vollersten *et al.*, 1998). The efficiencies estimated using particle size distribution and settling velocities as suggested in the Ministry of the Environment and Energy Stormwater Management Practices Planning and Design Manual of Ont., Can., which is used to design best management practices (BMP), were less than those estimated using the observed particle distribution and settling velocities estimated from these sites. Suspended solid removal estimation based on the manual would result in removal efficiencies more conservative than observed (Liang *et al.*, 1998).

Jones and Washburn (1998) mapped the three-dimensional distribution of dissolved and particulate components associated with stormwater runoff in Santa Monica Bay, Calif. The three major particles types in the bay were particles associated with the stormwater runoff, phytoplankton in the water column, and resuspended sediments.

Water quality and particle-size distribution were characterized from urban-stormwater runoff from two storms that indicated potential relationships between zinc (Zn)/organic carbon and iron (Fe)/macrocolloid (0.45 μm — 20 μm) pairs. Results also indicated that concentrations of particle ion number, organic carbon, suspended solids (SS), Fe, and Zn increased during storms but showed no evidence of the “first flush” (Characklis and Wiesner, 1997).

Solids-settling characteristics are very important for designing many CSO- and stormwater-sedimentation-control facilities. Pisano (1996) summarized more than 15 years of settling data obtained in the United States, separated by wastewater types.

CSOs

Servais et al. (1999) studied suspended solids, COD, and BOD in CSO affecting the River Seine (France). These basic measurements were compared with values of the biodegradable and refractory fractions of particulate and dissolved organic carbon. They found very similar numeric ratios between these parameters, even in areas having highly different conditions, making it possible for reasonable predictions of the biodegradable and refractory fractions of dissolved and particulate organic matter and of the bacterial biomass in combined sewage. CSO and source area runoff was investigated in Paris (France) by Chebbo et al. (1999). Resuspended material from the sewers contributed a larger fraction of the pollutants (suspended solids, organic matter, copper, and total hydrocarbons) than from the runoff during a runoff event. The results were quite different for lead, zinc, and cadmium whose main source was roof runoff due to corroding roofing materials.

Kerbs et al. (1999) found that the wave front that formed when a significant increase in flow occurred in a combined sewer was composed of the sewage that was present in the sewer before the flow rate increased and not the stormwater component that comprised most of the flow volume. By means of measurements and numerical simulations, they showed that this effect may cause the significant increase of dissolved constituents found in the first flush during CSO events. The vertical (rise) velocity of CSO floatable material, in addition to other basic measurements, was investigated by Cigana et al. (1999) in Montreal (Canada). They found that 80% of the floatables had a vertical velocity greater than 0.07 m/s.

Solids transport in sewers

Modeling the transport of sediment and other debris in sewers was investigated by Babaeyan-Koopaei et al. (1999). Using correct velocity distributions were found to be critical in order to obtain accurate predictions of sediment transport. A sensitivity analysis investigated the influence of some important parameters involved in the model, especially the drag coefficient, the lift coefficient, solid density, and pipe roughness. Arthur et al. (1999) proposed a new design approach to minimize sedimentation in sewers. They also compared the results of laboratory investigations with real sewer conditions. Johnstone et al. (1999) described on-going research concerning the disposal of large sanitary solids in combined sewers, assessing the relative sustainability of conventional disposal methods using an integrated, holistic approach, incorporating economics, sociology, life cycle data, and a risk assessment. They also described a project designed to study the behavior of the sanitary solids in the sewerage system through laboratory, field, and modeling studies. Skipworth et al. (1999) sampled and analyzed combined sewer sediment deposits and found coarse, loose, granular, predominantly mineral material that was overlain by a mobile, fine-grained cohesive-like sediment deposit in the invert of pipes. The erosion of this more mobile fraction was identified as the major source of the first flush of pollutants associated with CSO events. They presented a new approach to model the erosion and subsequent transport of these mobile sediments.

Rushforth et al. (1999) examined the relationships between the erosion of in-sewer organic deposits and the sediment composition. They found that sewer sediments consist of mixtures of organic and inorganic material and exhibit a much wider range of particle sizes and densities than typically assumed. Specifically, the characteristics of the fine organic sediment found in combined sewer deposits fall outside the applicable range of grain size and density for typically used sediment transport models. Their laboratory experiments showed that the addition of granular material in sewer deposits significantly increases the amount of organic material eroded, compared to a deposit composed entirely of organic material.

In-sewer processes

Hass and Herrmann (1999) examined the problems associated with gas transfer in sewer systems through laboratory and field reaeration studies using volatile tracers and conservative dye tracers. They found that traditional empirical models for reaeration in open channels worked well, with modifications to account for the sewage matrix used instead of clean water. During the field studies in sewer systems having low gas transport rates, concentrations close to the Henry's law equilibrium near the wastewater surface were found to minimize the transfer of the volatile gases from the wastewater to

the sewer gas. Huisman et al. (1999) studied oxygen mass transfer and the biofilm respiration rate in sewers. Oxygen transfer mass fluxes were found to be responsible for the major changes to wastewater as it flows to the wastewater treatment plant. They concluded that about 20% of the dissolved COD could be degraded in the investigated sewer system during the wastewater transport process.

Hvitved-Jacobsen and Vollertsen (1999) also developed a conceptual model for wastewater quality changes during transport in sewers. The model includes reaeration and major aerobic and anaerobic microbial processes in the water phase and in the sewer biofilm. Emphasis was placed on microbial transformations of the heterotrophic biomass and of the soluble and particulate fractions of the organic substrate. Vollersten et al. (1999) measured the effects of temperature and dissolved oxygen (DO) on the kinetics of microbial transformation processes of the suspended sewer sediment particles, suspended wastewater particles, and wastewater. The average Arrhenius constants found for sewer sediment particles and wastewater particles were found to differ significantly from the average Arrhenius constant found for the wastewater. However, no differences for the oxygen saturation coefficients were found between sewer sediment particles, wastewater particles, and wastewater. The anaerobic transformations of wastewater organic solids in sewers were studied by Tanaka and Hvitved-Jacobsen (1999), leading to a aerobic/anaerobic wastewater process model. During 19-25 hours of anaerobic conditions, a net production of readily biodegradable substrate, originating from hydrolyzable substrate, was observed. A small amount of methane production was also observed. Suguira et al. (1999) found that sewage stagnation at the downstream side of a separating tidal weir at a CSO discharge location caused an extraordinary generation of hydrogen sulfide, and associated nuisance odors.

Pollution Sources

General Sources

Hale et al. (2000) investigated the occurrence of nonylphenols (an endocrine disruptor often from laundry products) from a variety of outfalls, and found that the highest concentrations in the sediment (14,100 ug/kg) was detected near a federal facility's stormwater outfall. Sediment samples taken below an out-of-service sewage treatment plant indicated that nonylphenol persisted in the sediment. Hartmann et al. (2000) investigated the application of linear alkylbenzenes (LABs) as a molecular marker in marine sediments in Narragansett Bay. In the urban rivers at the head of the bay, the Providence River, Seekonk River, and Taunton River concentrations were locally high with a few values exceeding 2000 ng/g total LABs. The I/E (internal/ external C-12 isomers) ratio, a measure of the degree of degradation, indicated that treated sources (i.e. sewage effluents) and local fresh sources (e.g. combined sewer overflows and boat cleaning detergents) were major contributors of LABs to the rivers. The observed decrease in LAB concentration with distance downbay suggested that most of the LABs were deposited within a few kilometers of their source.

Storm runoff from the log handling area at the Port of Tauranga, North Island, N.Z., showed that the runoff may contain significant concentrations of resin acids, e.g., dehydroabietic acid (Tian et al., 1998). Seabed sediment samples were collected adjacent to the log handling area and analyzed to determine the extent of the resin acid deposition. The concentrations of conventional parameters, i.e., biochemical oxygen demand (BOD), chemical oxygen demand (COD) and SS, and 123 priority pollutants of stormwater runoff samples from a log storage and handling facility in La. were determined and no significant levels of priority pollutants were found. Only about 1—13% of COD was biodegradable and similar to SS concentrations, suggesting that effective control of SS will control COD as well (De Hoop et al., 1998b).

Hydrologists have known for some time that runoff can occur as the result of both saturation and infiltration excesses in soil containing nonpoint source (NPS) contaminants. Watershed areas that generated NPS polluted runoff needed to be identified prior to the design of basin-wide water quality projects (Endreny and Wood, 1999).

Hydrologic runoff was one of the main processes in which radionuclides deposited in the surface environment migrate widely in both particulate and dissolved forms. Amano et al. (1999) concentrated on the transfer capability of long lived Chernobyl radionuclides from surface soil to river water in dissolved forms.

Zaman (1999) found that the catchments with high intensities of development in close proximity to stormwater systems were found to be transporting more pollutants to receiving waters than other catchments. Dry-weather water quality monitoring was used to identify the most polluted areas of the catchment. Nirel and Revaclier (1999) used the ratio of dissolved Rb to Sr to identify and quantify the impact of sewage effluents on river quality in Geneva, Switzerland. Rubidium was present in larger quantities than strontium in feces and urine, making the ratio of these two elements

represents an effective tracer. This was especially true in regions where the natural Rb/Sr ratio was low (calcareous regions).

Gromaire-Mertz *et al.* (1999) collected stormwater runoff from 4 roofs, 3 courtyards and 6 streets on an experimental catchment in central Paris, France, and analyzed the samples for SS, VSS, COD, BOD₅, hydrocarbons, and heavy metals both in dissolved and particulate fractions. The street runoff showed large SS, COD and hydrocarbon loads, but the roof runoff had high concentrations of heavy metals. Wiese and Scmitt (1999) described urban stormwater contributions into large river systems. Their purpose was to develop a mass balance model for many stormwater pollutants, stressing nitrogen and phosphorus, the oxygen depleting substances and some heavy metals.

Iatrou *et al.* (1996) described the results of stormwater samples collected from the New Orleans drainage system. The sampling locations chosen represented residential, commercial, and industrial areas. Sakai *et al.* (1996) measured characteristics of storm runoff from road and roof surfaces and found the ratio of COD_{MN}: T-N to be in the range of 3:1 for roof-storm runoff and in the range of 7:1 for road-surface-storm runoff. They found the ratio of COD_{MN}:T-P to be 160:1. Most of the organic components and T-P in road-surface-storm runoff are insoluble, and road-surface-storm runoff contained soluble nitrogen (N), which could have been contributed from air pollutants.

Nowakowska-Blaszczyk *et al.* (1996) studied the sources of wet-weather pollutants in Poland. It was found that storm runoff from parking areas and streets had the greatest concentrations of suspended solids (SS), chemical oxygen demand (COD), five-day biochemical oxygen demand (BOD₅), and Pb, while phosphorus was mostly contributed from landscaped-area storm runoff. Storm runoff from roofs covered with roofing paper was also a significant contributor of many pollutants.

Atmospheric

In a study on the influence of atmospheric deposition on the concentrations of mercury, cadmium and PCBs in urban runoff, Atasi *et al.* (2000) found that atmospheric deposition was the primary source of these compounds in runoff from controlled surfaces. The authors argued that the contribution of atmospheric deposition must be accounted for both in modeling of pollutant sources, but also in planning for pollution prevention.

Atmospheric deposition, often contaminated to varying degrees, can be a significant source of phosphorus to South Florida's aquatic system. Outliers were detected by field notes, derived from visual inspection of the samples, and statistics, based on simple linear regression used for additional screening. Based on detected outliers in the data from 115 monitoring sites, a lumped cutoff value, used for further quality control, of 130 Fg/L was determined (Ahn, 1999).

Garnaud *et al.* (1999) studied heavy metal concentrations in dry and wet atmospheric deposits in Paris, France, for comparison with urban runoff. Samples were continuously collected for 2 to 13 months at each of four test sites. Comparisons of median values of metal concentrations showed that rainwater contamination with heavy metals was only slightly higher in the center of Paris than at Fontainebleau (48 km SE of the city) which illustrates the medium range transport of atmospheric contamination.

Atasi *et al.* (1999) used specialized sampling equipment and ultra-clean analytical methodology to quantify the concentrations or fluxes of mercury, cadmium, and polychlorinated biphenyl in ambient air, precipitation, runoff, sanitary sewage, and treated sewage in Detroit, Michigan. Atmospheric deposition was found to be the primary source of the mass of Cd, Hg, and PCB, in runoff from the controlled surfaces. Shiba *et al.* (1999) also investigated the role of atmospheric deposition as a source of urban runoff contaminants. They found that the chemical substances in rainwater were an important pollution source.

Detailed characterization of 71 individual polychlorinated biphenyl (PCB) congeners in the waste streams at the 26 New York City (NYC) and N. J. water pollution control plants (WPCP) showed that of the estimated 88 kg of PCB released annually by the WPCP, roughly 3% was contributed by CSO due to heavy precipitation (Durell and Lizotte, 1998). Atasi *et al.* (1998) analyzed atmospheric and runoff samples to determine wet and dry deposition and the relative contribution of deposition to runoff pollutant mass. Ahn (1998) recorded the total phosphorus (P) concentrations in south Fla. rainfall at weekly intervals with a detection limit of 3.5 µg/L. Air deposition was found to be the primary source of Cd, Hg, and PCB mass in runoff at the controlled sites in the study. Phenols were present at high concentrations in urban rainwater and ambient air (Allen and Allen, 1997).

Results from ten watersheds indicated organic P and carbon (C) correlated with the concentration of suspended particles, which differed among the watersheds. Recent estimates also suggest that 40% of the nitrogen (N) loading to the Chesapeake Bay watershed comes from atmospheric deposition, 33% from livestock waste, and 27% from fertilizer (Jordan *et al.*, 1997).

Pankow *et al.* (1997) proposed that frequent observations of the fuel additive methyl-tert-butyl ether (MTBE) in shallow urban groundwater may be due to atmospheric deposition accumulated during precipitation events and subsequent infiltration of stormwater. A one-dimensional mathematical model simulated five scenarios with varying conditions of precipitation, transport, source concentrations, and evapotranspiration and indicated that significant contributions of the compound may be coming from the atmosphere.

Roof Runoff

Zobrist *et al.* (2000) examined the potential effects of roof runoff on urban stormwater drainage from three different types of roofs: an inclined tile roof, an inclined polyester roof and a flat gravel roof. Runoff from the two inclined roofs showed initially high (“first flush”) concentrations of the pollutants with a rapid decline to lower levels. The flat gravel roof showed lower concentrations of most of the pollutants because of the ponding of the water on the roof surface acting like a detention pond. Pollutant loadings was similar to atmospheric deposition, with the exception of copper from drain corrosion (rate about 5 g/m²/yr).

Tobiason and Logan (2000) used the whole effluent toxicity (WET) to characterize stormwater runoff samples from four outfalls at Sea-Tac International Airport. Three of the four outfalls met standards; the source of the toxicity at the fourth outfall was found to be zinc-galvanized metal rooftops. Typically, more than 50% of the total zinc in the runoff was in dissolved form and likely bioavailable.

Foerster (1999) and Foerster *et al.* (1999) reported on studies investigating roof runoff as stormwater pollutant sources. Runoff samples were taken from an experimental roof system containing five different roofing materials and from house roofs at five different locations in Bayreuth, Germany. It was found that local sources (e.g. PAH from heating systems), dissolution of the roof systems’ metal components, and background air pollution were the main sources of the roof-runoff pollution. They found that the first flush from the roofs often was heavily polluted and should be specially treated. They concluded that roofs having metal surfaces should not be connected to infiltration facilities as concentrations of copper and zinc far exceed various toxicity threshold values. They also examined a green (vegetated) roof for comparison. These roofs were found to act as a source of heavy metals which were found to be in complexes with dissolved organic material. Leaching from unprotected zinc sheet surfaces on the green roofs resulted in extremely high zinc concentrations in the runoff. In contrast, the green roofs were a trap for PAH.

Sakakibara (1996) investigated roof-runoff quality in Ibaraki prefecture, Japan, in order to determine the feasibility of using roof runoff in urban areas for various beneficial uses. Eighty three samples were collected during one year and analyzed for pH (averaged 6.1), BOD₅ (averaged 1.6 mg/L), COD (averaged 3.2 mg/L), and SS (averaged 12 mg/L). It was concluded that roof-runoff could be used for toilet flushing and landscaping watering with minimal treatment or problems. Heavy metals and major ions in roof-runoff were investigated by Förster (1996) in Bayreuth, Germany. It was found that the major ions were from the rain, while very high Cu and Zn concentrations were from metal flashings used on the roofs. It was concluded that the best option would be to abandon the use of exposed metal surfaces on roofs and walls of buildings.

Highway and other Roadway Runoff

Since urban roads are typically directly connected to the drainage system and therefore respond quickly to storm events, the quality of urban road runoff in the Sydney, Australia, region was investigated by Ball (2000a). This paper also proposed guidelines for estimating the transportable trace-metal loading from road surfaces. Ball *et al.* (2000) showed that the quality of the runoff resulting from the construction of a new highway intersection in Australia could be improved by using treatment devices such as detention ponds and sand filters. Hirsch (2000) reported on the development of a TMDL for Straight Creek in Colorado due to the sediment and pollutant loads contributed to the stream by Interstate 70 runoff. The interstate construction increased erosion in the stream due to the significant cut-and-fill, as did the snowy winter road conditions which required extensive sand applications. An investigation by Drapper *et al.* (2000) showed that the pollutant concentrations (heavy metals, hydrocarbons, pesticides, and physical characteristics) in ‘first flush’ road runoff in Brisbane in southeast Queensland, Australia was within the ranges reported internationally for highways. Traffic volumes were the best indicator of road runoff pollutant concentrations, with interevent duration also being statistically

significant factor. Exit-lane sites were found to have higher concentrations of acid-extractable copper and zinc, likely due to brake pad and tire wear caused by rapid deceleration, and laser particle sizing showed that a significant proportion of the sediment in runoff was less than 100 μm . Krein and Schorer (2000) investigated heavy metals and PAHs in road runoff and found that, as expected, an inverse relationship existed between particle size and particle-bound heavy metals concentration existed. However, particulate-bound PAHs were found to be bimodally distributed. Three-ring PAHs were mostly found in the fine sand fraction, while six-ring PAHs were mostly concentrated in the fine silt fraction. Sutherland et al. (2000) investigated the potential for road-deposited sediments in Oahu, Hawaii, to bind contaminants, and thus transporting these bound contaminants to the receiving water as part of the runoff. In the sediment fractions less than 2 mm in diameter, the origins of the aluminum, cobalt, iron, manganese and nickel were determined to be geologic. Three of the metals concentrations, copper, lead and zinc, were found to be enhanced by anthropogenic activities. Sequential extraction of the sediment determined the associations of the metals with the following fractions: acid extractable, reducible, oxidizable, and residual).

An overview of the National Cooperative Highway Research Program (NCHRP) upcoming work was presented by Stein et al. (2000). This presentation included an evaluation of past work on stormwater runoff from transportation facilities and a prioritization of future research in this area.

Walker et al. (2000a) reviewed the on-going water quality assessment program implemented by the San Diego region of the California Department of Transportation (Caltrans). Constituents of concern were being targeted for monitoring and potential remediation. The thermal enhancement of stormwater runoff by paved surfaces was investigated by Van Buren et al. (2000a and 2000b). The results from the test-plot studies were used to help develop, calibrate and verify the wet-weather model TRMPAVE, a mathematical model that uses an energy balance to predict the temperature of the runoff. Glenn et al. (2000) found that the snow residuals along highways had high levels of particulate and solid matter, likely from nearby vehicular traffic. Snow also accumulated traffic-based pollutants to a greater degree.

In the Kerault Region of France, the effects of pollution were studied using solid matter from a section of the A9 motorway. This study analyzed both settled sediments from collecting basin and characteristics of sediments in the water column during and after eight storm events between October 12, 1993, and February 6, 1994. Settled sediments were used to measure particle sizes, mineral content, and related characteristics, whereas water samples were used to document total suspended solids, mineral content, and heavy metals (Andral et al., 1999).

Runoff from highways contains significant loads of heavy metals and hydrocarbons, according to German regulations it should be infiltrated over embankments to support groundwater recharge. To investigate the decontaminating effect of greened embankments, soil-monoliths from highways with high traffic densities were taken. Soils were analyzed to characterize the contamination in relation to distance and depth for lead, zinc, copper, cadmium, PAH and MOH (Dierkes and Geiger, 1999).

The quality of highway runoff monitored in the Austin, Tex. area at three locations on the MoPac Expressway were similar in constituent concentration to median values compiled in a nationwide study of highway runoff quality (Barrett et al., 1998a). A grassy swale at one site which had a lower runoff coefficient due to infiltration reduced concentrations of most constituents in runoff. The pollutants available for transport during storm events of a suburban road in the eastern suburbs of Sydney, Aust. were significantly different from published data for North Am. (Ball et al., 1998). Both rain and wind events lowered the available pollutant constituent mass on the road surface. Fourteen composite samples of Marinette, Wis. stormwater, as well as baseflow samples, were analyzed to determine requirements for a National Pollutant Discharge Elimination System (NPDES) permit and the results indicated similarity to stormwater found in other communities (Scholl and Lauffer, 1998). Measurements of conductivity and turbidity taken in a study of the Crum Creek which runs through the suburbs of Philadelphia, Pa. indicated two stages during the first three hours of wet weather runoff: a dissolved solids flush followed by a suspended solids (SS) flush (Downing and McGarity, 1998).

In San Francisco, Calif., vehicle emissions of both ultrafine ($< 0.12 \mu\text{m}$) and accumulation mode ($0.12 - 2 \mu\text{m}$) particulate polycyclic aromatic hydrocarbons (PAH) are derived from diesel vehicles while gasoline vehicles emit higher molecular weight PAH primarily in the ultrafine mode. Heavy duty diesel vehicles were found to be important sources of fine black carbon particles (Miguel et al., 1998). In a European study, 90% of the particles from a contaminated highway runoff catchment were smaller than 100 μm . The constituents of the contaminants smaller than 50 μm were further analyzed by X-ray diffraction, thermogravimetry and specific mass and contained 56% clay, 15% quartz, 12% chalk, 9% organic matter, 5% feldspars, and 2% dolomite (Roger et al., 1998).

Several researchers investigated roadway storm runoff as a nonpoint pollution source and reported their results at the 7th International Conference on Urban Storm Drainage in Hannover (Sieker and Verworn, 1996). Wada and Miura (1996) examined storm runoff from a heavily traveled highway in Osaka, Japan. A significant “first-flush” for COD was found and the amount of small rubber pieces from tire wear in the highway storm runoff was more than 20 times greater than for an “ordinary” road. The primary factors affecting storm runoff concentrations were the amount of traffic (and related exhaust emissions and tire wear) and the fraction of the total traffic that was comprised of trucks and buses. Montrejaud-Vignoles *et al.* (1996) collected storm runoff from a heavily used six-lane motorway in the Mediterranean area of France. The very irregular rainfall in this area and associated very-long dry periods can result in storm runoff that is much more polluted than elsewhere in France. As an example, during the one-year study, a single rain of only 10 mm but having an antecedent-dry period of 35 days, produced more than 12% of the annual COD discharges. Ball *et al.* (1996) examined roadway pollutant accumulations in a suburb of Sydney, Australia. It was concluded that the local heavy winds have a significant effect on pollutant accumulations that commonly available stormwater models do not consider, and that historical United States’ data on roadway-pollutant accumulations are much greater than found in their area. Sansalone and Buchberger (1996) studied metal distributions in stormwater and snowmelt from a major highway in Cincinnati, OH. Zn and Cd were mostly in filterable (dissolved solids) forms in the storm runoff, while lead was mostly associated with particulates.

Deicing Discharges

Deicing salt (NaCl) fate was determined from retention and loss in snow cover adjacent to a 14 km section of the highway in southern Ontario during the 1994-1995 winter. Almost all applied NaCl reached the soil surface via direct runoff and infiltration of saline water from the road into the shoulder and right-of-way, and transfer of salt to snow cover adjacent to the highway and release during snow melt (Buttle and Labadia, 1999).

Paschka *et al.* (1999) studied the water-quality effects associated with the extensive use of water-soluble iron cyanide compounds used as anticaking agents in road salt. Although available information did not indicate a widespread problem, it was also clear that the water-quality effects of cyanide in road salt had not been adequately examined.

During the winter of 1995-1996, deicing chemicals (approximately 3×10^6 L of ethylene glycol, 0.5×10^6 kg of urea, and 23×10^3 kg of potassium acetate) were spread on the Pittsburgh (Pa.) International Airport and presumably drained into Montour Run, a nearby stream. The metabolism of glycols and urea exerted a strong BOD in receiving water and elevated concentrations of ammonia (NH_3) (Koryak *et al.*, 1998).

Complex ferrocyanide compounds, which can break down into free, toxic, cyanide compounds, are added to salt to prevent caking (Novotny *et al.*, 1998a). Salt also decreased partitioning between adsorbed and dissolved metals which increased dissolved metals in snowmelt. A dynamic model was developed and calibrated to calculate daily loads and concentrations from snowpiles of three northern cities using salt for deicing (Novotny *et al.*, 1998b). Snowmelt runoff from an urban watershed can produce density current intrusions in a lake (Ellis *et al.*, 1997). Snowmelt runoff entering Ryan Lake in Minneapolis, Minn. increased electrical conductivity, salinity and density with salt spread on urban streets as the source of the salinity.

Treated Wood

Treated wood has periodically been identified as a potential source of toxicants in stormwater but few studies have specifically examined its role. Weis and Weis (1996) examined the leaching potential of Cu-Cr-As (arsenic) mixture (CCA) treated wood in Chesapeake Bay. Sediment and benthos samples were analyzed for Cu, Cr, and As at varying distances from treated-wood bulkheads at test and control sites. In general, sediment metal concentrations decreased with distance from the treated-wood bulkheads but not at the control stations. The species diversity and the number of individual species were also less at the treated-wood site at the poorly flushed location but not at the control area having similar flushing conditions.

Wastewater, CSOs, and Sanitary Sewer Overflow Sources

Lessard and Michels (2000) examined the effects of CSO basin discharge on the water quality in the Menominee River in 1997. Based on the data collected, the overflow from the CSO retention basin does meet the Michigan Water Quality Standards during the overflow discharge events, with the basin providing the equivalent of primary treatment plus disinfection. The loadings of most of the pollutants, including nutrients, metals and suspended solids, were insignificant compared to background. The CSO basin effluent also did not appear to impact the dissolved oxygen in the river to the

point where the DO fell below standards.

CSO and urban streams receiving CSO in the Pittsburgh, Pa. area were tested for *cryptosporidium* and *giardia*. Data suggested CSO are a significant source in small streams (Stadterman et al., 1998).

The EPA (1996f) conducted case studies to examine the effects of CSOs on the biological integrity of some example streams in Ohio and New York using rapid-bioassessment protocols. Results were compared with historical assessments of the same streams. Drinnan *et al.* (1996) presented data that showed the application of rating systems developed to identify discharges that have public-health or environmental concerns and provide a protocol for initiating mitigative measures in Victoria, BC, Canada. The number of discharges designated as high priority because of their effects on public health has decreased steadily between 1992 and 1995 and the number of bathing beaches posted with a health advisory has decreased from 28 in 1969 to none in 1995. *Water Environ. & Technol.* (1996b) reported that the fecal coliform counts decreased from about 500/100 mL to about 150/100 mL in the Mississippi River after the sewer-separation program in the Minneapolis and St. Paul, MN area. Combined sewers in 8,500 ha were separated during this 10-year, \$332 million program.

Results from sediment samples collected adjacent to each of four CSO along the lower Passaic River of New Jersey indicated that sediments proximate to the CSO outfalls were contaminated with a range of chemicals including toxic metals, PAH, PCB, pesticides, and other organic chemicals. The spatial distribution of these contaminants strongly suggested that the CSO were the primary source of contamination in sediments near these outfalls (Iannuzzi *et al.*, 1997).

Inappropriate Discharges

McGee et al. (2000) investigated the potential sources of indicator bacteria that closed a portion of Huntington State Beach in Orange County, California. The approach used was termed a “risk-based sanitary survey,” and the investigation used both state-of-the-art technologies (radar, sonar, and infrared imaging) and conventional techniques (geo-probes, television inspection of the sewers, and monitoring wells). White et al. (2000) investigated the effects of land use change and resulting bacterial concentrations on shellfish closures in Jump Run Creek in North Carolina. The results of this project showed that the likely sources of the elevated bacterial concentrations (high during wet weather, moderate during dry weather) was the area draining an older, medium density residential neighborhood (single family homes, trailer park with two malfunctioning septic tanks and more than 100 pets, plus wildlife). Dye studies in the area indicated that flow through area was too small for bacterial mortality to occur.

The combined use of sterol biomarkers and bacterial indicators showed that during wet weather, all sites sampled in the storm drainage system of Geelong, Victoria, Aust. were subject to human fecal contamination. Ratios of coprostanol to bacterial indicators were similar to those for samples collected from nearby sewer mains (Leeming et al., 1998).

Sangal *et al.* (1996) conducted a feasibility study for the Rouge River National Wet Weather Demonstration Project to evaluate the applicability of the stable-isotope approach to identify illicit connections in three mini-watersheds in or near Wayne County, MI. The results indicated that the isotopic technique is extremely cost-effective and robust for distinguishing between local groundwater and water derived from domestic and industrial or commercial sources.

Baltimore, MD as part of their NPDES permit, examined their storm-drainage system for sources of illicit entries (Stack and Belt, 1996). About one third of the 344 small subwatersheds in the city have been targeted as potential sources of toxicants from illicit entries, based on analyses of surfactants, phenols, ammonia, Cu, Pb, Zn, and total petroleum hydrocarbons, with eight sources specifically identified.

Industrial Sources

Akan et al. (2000) noted that a significant pollutant loading to the adjacent receiving water can occur due to runoff from marine drydocks. The authors modeled the quantity and quality of marine drydock runoff by combining the two-dimensional kinematic wave and convective transport equations with an empirical formula for washoff. Lewis et al. (2000) reviewed stormwater-runoff monitoring data from industrial facilities discharging into the upper San Gabriel watershed in the Los Angeles region. The results of this review showed that while industrial facilities occupy less than 1% of the watershed area, they contribute between 10% and 70% of the total copper and between 15% and 60% of the total zinc loads. Moreno-Grau et al. (2000) investigated the heavy metal content of atmospheric aerosols and suspended particulate matter from industrial areas in Cartagena. The industries contributing to the atmospheric metals contamination included power plants, oil refineries, non-ferrous metals, fertilizer plants and a shipyard.

Samples of stormwater runoff from three sawmills on Vancouver Island, British Columbia, Canada, were tested for acute toxicity with juvenile rainbow trout. Causes of toxicity were investigated using toxicity identification evaluation techniques; specifically, treatment with the chelating agent EDTA (Bailey et al., 1999a). Samples of stormwater runoff from nine sawmills in British Columbia, Canada, were also tested for acute toxicity with juvenile rainbow trout over a 23-month period. Toxicity was attributed to divalent cations, particularly zinc, in 32 of the samples. Toxicity in the remaining samples was largely attributed to tannins and lignins and was associated with areas of bulk log handling (Bailey et al., 1999b).

The EPA has released NPDES stormwater-monitoring data from industries using agricultural products (Amick, 1996). Data from facilities representing the food, tobacco, textile mill, apparel, and other industries and appropriate best management practices for reducing or eliminating the pollutants are presented. Su and Christensen (1996) developed a chemical-mass-balance model to identify sources of polychlorinated dibenzo-p-dioxin (PCDD) and dibenzofuran (PCDF) in a sediment core from the Baltic Sea that spanned the time period from 1882-1985. The results indicate that coal-fired-power plants, municipal incinerators, and pentachlorophenol-containing matter contribute significantly to the measured PCDD and PCDF.

Hall (1996) collected samples from two estuarine wetlands in highly urbanized areas to determine if chromite ore processing residue surrounding one site contributes to significantly higher chromium (Cr) concentrations in biotic and abiotic media relative to those at a reference site. Although concentrations of Cr, Cu, and Pb were significantly higher in sediment samples from the study site compared to the reference site, no pattern of higher metals concentrations in biotic samples from the study site was found.

Line *et al.* (1996) examined stormwater from ten industrial sites in North Carolina for a broad list of conventional- and metal- and organic-toxic-substance-pollutant parameters. Automobile-salvage-yard runoff had the highest metal concentrations except for the wood-preserving sites which had the highest chromium concentrations. Other pollutants did not vary significantly between different types of industrial operations.

Specific Pollutant Sources

Litter

Williams and Simmons (1999) investigated the sources of litter in and along the river Taff, South Wales, UK. The greatest inputs of sewage-derived solids were introduced to the river by malfunctioning CSO. While sewage-derived material constituted approximately 23% of all items on the river Taff, large quantities of waste, especially plastic sheeting, originated from fly tipping sites (illegally dumped rubbish in public places).

Sediment

Benoit et al. (1999a) studied sources of sediment entering Jordan Cove, Connecticut. Recent sediment accumulation rates were found to be decreasing (from 0.84 cm/yr to 0.40 cm/yr) but were slightly faster than relative sea-level rise at this site (0.3 cm/yr). Long Island Sound was found to be an important source of sediment to the cove; a minor part of total sediment was supplied from the local watershed. Benoit et al. (1999b) also studied sources and the history of heavy metal contamination and sediment deposition in Tivoli South Bay, Hudson River, New York. The measured sedimentation rate ranged from 0.59 to 2.9 cm/yr suggesting that rapid accumulation occurred during the time period represented by the length of the cores (approximately the past 50 yrs). The sources of this material were expected to be upland streams, or the Hudson River, during storm events. Concentrations of Pb, Cu and Zn correlated with each other within individual cores at five of the six sites tested, suggesting a common proximate source. Nelson (1999) described the sediment budget of Issaquah Creek, a 144 km² mixed-use, urbanizing watershed near Seattle, WA. The water quality of Lake Sammamish, located at the outlet of the basin, was degrading with time, and fine sediment entering the lake from the watershed was a likely source of phosphorus during periods of lakeanoxia. Another potential in-channel concern was the effect of fine sediment on spawning gravel for the salmon species that occupy Issaquah Creek. The sediment balance was being used to identify the major sources of sediment, and thus guide the most effective remedial measures.

Nutrients

The research conducted by Sonoda et al. (2000) investigated the impact of land use on streamwater nutrient concentrations in an urbanizing watershed in Oregon. During the dry season, soluble reactive phosphorus (SRP) was correlated with light industry land use, while during the wet season, SRP was correlated with light industry, single family residential and mixed residential land uses. During the dry season, nitrate-plus-nitrite was correlated with rural, and heavy

and light industry land uses, while during the wet season, $\text{NO}_3 + \text{NO}_2\text{-N}$ was correlated with rural and heavy industry land uses.

Basnyat et al. (1999) described a methodology to assess the relationships between land use and nitrate and sediment concentrations in streams in the Fish River, Alabama watershed. Residential and other developed urban areas were identified as the largest contributors of nitrate in the area, while active agriculture was identified as the second largest contributor.

Waschbusch et al. (1999) investigated sources of phosphorus in stormwater and street dirt from two urban residential basins in Madison, Wisconsin. They collected numerous sheetflow runoff samples from throughout the test watersheds and used SLAMM, an urban stormwater quality model, to quantify the significance of the different phosphorus sources. Lawns and streets were found to be the most significant sources of phosphorus in the test basins, contributing about 80% of the total annual loading. Peters and Donohue (1999) examined nutrient concentrations and fluxes in tributaries to the Swan-Canning estuary, Western Australia. In addition to the rapid mobility of nutrients in stream water from agricultural areas during the wet season, urban area storm drains typically had high nutrient concentrations, and were also an important source of nutrients to the estuary. Sonoda et al. (1999) described correlations between land use and nutrient inputs to an urbanizing Oregon stream. In the urbanizing areas, possible nutrient sources included fertilizer applied to yards, in addition to roof runoff, various household chemicals, and street runoff.

Manure or compost from beef cattle feedlots can be an excellent source of nutrients and organic matter when added to soils, but they can also pollute runoff. Eghball and Gilley (1999) determined the effects of simulated rainfall on runoff losses of P and N, and EC and pH following application of manure and compost to a Sharpsburg silty clay loam (fine smectitic, mesic Typic Argiudoll) soil having grain sorghum [*Sorghum bicolor* (L.) Moench] and winter wheat (*Triticum aestivum* L.) residues.

A study has been conducted on a 4% slope during 1991 to 1993 at Belie Mina, Alabama, on a Decatur silty clay (clayey, kaolinitic, thermic Rhode Paleudult) to determine effects of broiler litter CBL on seasonal transport losses of nutrients and heavy metals in surface water (Wood et al., 1999). Rainfall, slopewash (the erosion of soil particles), surface runoff and fine-litter transport at humid-tropical steep land sites in the Luquillo Experimental Forest, Puerto Rico (18 degrees 20' N, 65 degrees 45' W) were measured from 1991 to 1995 (Larsen et al., 1999). To identify critical sources of P, Sharpley et al. (1999) investigated chemical and hydrologic factors controlling P export from a mixed land use (30% wooded, 40% cultivated, 30% pasture) 39.5 ha watershed in east-central Pennsylvania.

Sauer et al. (1999) reported that grazing animal excretions were not as significant a source of nutrients to runoff water as was poultry litter; such treatments receiving poultry litter had significantly higher losses of nutrients, including those most commonly associated with surface water indices.

Mass balance calculations for a treated and untreated watershed at the BBWM in Maine showed that annual and cumulative retention of experimental N amendments has leveled off at about 80% after nine years of treatment. The annual retention of treatment S has declined to less than 34% after nine years, with the cumulative retention below 60% over the course of the experiment (Kahl et al., 1999). Soils that contained high P levels could become a primary source of dissolved reactive P (DRP) in runoff, and thus contribute to acceleration eutrophication of surface waters. Because results might differ on other soils, runoff studies were conducted on three additional Ultisols to identify the most consistent STP method for predicting runoff DRP levels, and determine effects of site hydrology on correlations between STP and runoff DRP concentrations (Pote et al., 1999).

An investigation of nonpoint sources (NPS) of P loads to Lake Champlain (Vt./N.Y.) revealed that 18% of the P load came from urban sources which only represented 3% of the contributing Lake Champlain Basin (Meals and Budd, 1998). Other sources included agricultural (66%) making up 28% of the basin, and forest (16%) making up 62% of the basin. An analysis of the Middle Huron River Watershed concluded that the highest concentration of P in runoff came from urban residential areas (Brenner and Rentschler, 1998). A watershed for a small lake in suburban Boston, Mass., supplied over 90% of the P in the lake during a year with normal precipitation and only 15% of the P during a dry year. The P not supplied by the watershed was supplied by a large population of Canada Geese directly to the lake (Moore et al., 1998a).

Choi and Blood (1999) reported the increase of urban growth along coastal states, resulting in the growth of urban non-point source nitrogen runoff to be a major contributor to coastal and estuarine enrichment.

Sediments in the rivers and basins around Washington, D.C. have high concentrations of phosphorus (P) and based on geographic distributions are largely derived from urban stormwater runoff and municipal wastewater (Huanxin *et al.*, 1997). Concentrations of total sedimentary P ranged from 24 μm — 56 μm P/g-dry weight and were highest near combined sewer outfalls and suggested that P from natural sources is small compared to anthropogenic inputs.

Herrmann and Klaus (1996) examined nutrient discharges to rivers in Germany from urban-area-drainage systems. Groundwater was the single largest source of nitrogen, while municipal wastewater was next. Other sources (runoff, drainage water, erosion, stormwater, and industrial waters) were all much smaller. Municipal wastewater was the largest source of phosphorus, while erosion sources was next, with the other sources much smaller.

Bacteria

De Luca-Abbott *et al.* (2000) used enterococci to trace the spatial and temporal impacts of stormwater discharges from an outfall in northeastern New Zealand. Both seasonal and temporal trends in *enterococci* concentrations were noted, with the maximum contamination being found with the high winter rainfalls and near the outfalls. The occurrence and possible sources of *Giardia* and *Cryptosporidium* in Paris rivers were investigated by Rouquet *et al.* (2000). The results showed that non-point sources likely influenced parasite concentrations in the rivers. Parasite sedimentation was high, as was the potential for resuspension by urban runoff. Ramirez Toro *et al.* (2000) presented the study design for investigating water quality in La Parguera in relation to onshore development, stormwater outfalls, and mangroves and sewage treatment plants in the vicinity. Samples were analyzed for the following constituents: bacteriological indicators (total and fecal coliforms, *Escherichia coli*, *enterococcus*), total suspended solids, chlorophyll, light attenuation (light reaching the bottom compared to surface) and nutrients (NH_3 , NO_3 , NO_2 and PO_4).

Young and Thackston (1999) studied fecal bacteria in urban tributaries in Nashville, Tennessee. The urban streams (unaffected by sewage discharges) were much higher in sewered basins than in nonsewered basins and the fecal bacteria densities were related to the density of housing, population, development, percent impervious area, and apparent domestic animal density. Preliminary fecal bacteria data collected for surface runoff samples in these urban neighborhoods indicated that a relationship existed between various urban land uses and bacterial loading.

Rainfall increased levels of both *giardia* cysts and *cryptosporidium* oocysts in the Delaware River through its influence on turbidity, flow volume, and possibly other unidentified factors (Atherholt *et al.*, 1998). The sources included river bottom sediments, stormwater runoff, direct inputs from domestic or wild animals and possibly WPCP. Samples of point and nonpoint discharges in a creek in Nashville, Tenn. were analyzed for fecal coliforms during four wet-weather events. Modeling showed that bacterial contamination originated minimally (14%) from SSO and mostly from other sources including urban runoff, and upstream agricultural, wildlife and septic tank sources (Goffinet *et al.*, 1998). Duke and Kihara (1998) report that available information supports an improved regulatory approach to nonstorm discharges to storm drains. Some discharge types, including condensate from machinery and firefighting equipment discharges, are believed to represent minimal threats to receiving-water quality while runoff from landscape irrigation is an unregulated discharge that may represent a threat to receiving-water quality and is fairly widespread. During an investigation to identify major sources of bacteria that were keeping the town of Greenwich, Conn. beaches closed, the primary identified WWF sources were an outdoor sewage sludge composting facility and a regional municipal solid waste transfer station (Audet, 1998).

Gibson *et al.* (1996) reported an overall increase in fecal coliform densities during wet-weather compared with dry weather for the Ohio River and the physical parameters (temperature, pH, and conductivity) do not correspond to CSO discharges into this large river. Lyons *et al.* (1996) reported that the intensive monitoring conducted could not support the hypothesis that depressed levels of dissolved oxygen found during the low-flow, summer months are associated with discharges from CSOs in the Cincinnati, OH area. Van Der Tak *et al.* (1996) presented the results of New Jersey's Tri-City Sewerage Authority's monitoring program of CSOs for Hg, SS, BOD_5 , and fecal coliform. Clean-sampling techniques were used in order to detect mercury at extremely low levels.

Toxicants

Toxicity testing was performed by de Vlaming *et al.* (2000) in order to identify chemical causes and sources of contamination. Urban runoff was found to be toxic to *Selenastrum*. The overall results indicated that the whole-effluent toxicity (WET) tests, when combined with traditional chemical analyses, were beneficial in locating sources of toxicity within a watershed.

Pitt et al. (1999) investigated typical toxicant concentrations in stormwater, the origins of these toxicants, and storm and landuse factors that influenced these toxicant concentrations. Nine percent of the 87 stormwater source area samples analyzed were considered extremely toxic (using the Microtox™ toxicity screening procedure). Thirty-two percent of the samples exhibited moderate toxicity, while fifty-nine percent of the samples had no evidence of toxicity. Vehicle service and parking area runoff samples had many of the highest observed concentrations of organic toxicants. All metallic toxicants analyzed were found in the analyzed samples. Marsalek and Rochfort (1999) also investigated the toxicity of urban stormwater and CSO. Acute toxicity, chronic toxicity and genotoxicity of stormwater and CSO were studied at 19 urban sampling sites in Ontario, Canada, using a battery of seven bioassays. Most frequent responses of severe toxicity were found in stormwater samples (in 14% of all samples), particularly those collected on freeways during the winter months. Compared to stormwater, CSO displayed lower acute toxicity (7% of the samples were moderately toxic, and none of the samples was severely toxic).

Huber and Quigley (1999) studied highway construction and repair materials (e.g. deck sealers, wood preservatives, waste-amended pavement, etc.) for their chemical and toxicological properties and leaching characteristics. *Daphnia magna* (a water flea) and the algae *Selenastrum capricornutum* were used for the toxicity tests. Leaching was evaluated as a function of time using batch tests, flat plate tests and column tests, as appropriate for the end-use of the highway material.

Malmquist et al. (1999) investigated the sources of pollutants discharging to Lake Trekanten, Stockholm, which receives stormwater from residential and traffic areas. Lead, cadmium, copper, zinc, phosphorus, and PAH in the stormwater from the catchment area were quantified by a source model. It was concluded that building materials were the dominant sources for copper and important sources for zinc. Source control measures, including covering copper-plated roofs, decreasing traffic, and changes of vehicle materials, were expected to reduce discharges of copper to less than a third of current levels.

Potential contributions of urban runoff pollutants to surface sediments of the Passaic River in New Jersey were investigated by Walker et al. (1999). Mass loading calculations demonstrated that urban runoff was a significant source of the metals observed in the sediments, and that PAH and DDT sediment loadings could, in some cases, be accounted for by urban runoff. Observed sediment loads for PCB, however, were significantly higher than were estimated from urban runoff.

Heavy metals

A study of heavy metal concentrations in sediments from Australian estuaries and the continental shelf by Birch (2000) showed that the concentration of metals was significantly higher in the estuaries than along the continental shelf. Also, the estuaries were found to have sediment metals concentrations that were related to the degree of urbanization/industrialization in the watershed. High metals concentrations, including Pb and Zn in Port Jackson (Sydney, New South Wales) which were at levels expected to have adverse environmental/biological effects, were found in the fluvial sediments, indicating that metals are still being added to the estuaries, potentially through stormwater runoff (including land reclamation leachate). Webster et al. (2000) analyzed the sources and transport of trace metals in the Hata River catchment and estuary in New Zealand. They found that the recently deposited estuarine sediment has elevated levels of Cu, Pb, and Zn from the more densely-populated areas, city stormwater drains and the Cu-containing antifoulants used in the marina. All metals were transported in both dissolved and particulate form in the tributaries, with lead being shown to bind most effectively to the sediment. Levesque and De Boer (2000) investigated the impact of a large urban center on the trace metal chemistry of a surficial fine-grained sediment in the South Saskatchewan River, Canada. No effect from the urban center on the metals content of the sediment was seen - with the exception of uranium, whose concentration was measurably greater below the urban center. Smith and Swanger (2000) investigated the impact of leaching of lead-free solders in construction waste and found that alloys containing antimony had leachate concentrations above regulatory limits. Alloys containing silver also potentially could impact the environment if entrained in stormwater runoff.

Birch et al. (1999) investigated the sources of heavy metals in stormwater draining into Port Jackson, Sydney, Australia. Road dust from streets with different traffic densities in the catchment were highly enriched with Cu, Pb, and Zn. Soils also contained high concentrations of these metals over extensive areas of the catchment. Preliminary data suggests that roads and soils were probably important in supplying heavy metals to the estuary but the contributions of atmospheric deposition and contaminated sites had not yet been evaluated.

Land applications of organic soil amendments can increase runoff concentrations of metals such as Fe and Zn, metalloids such as B and As, and non-metals such as P and S that have the potential for causing adverse environmental impacts. Aluminum sulfate, or alum ($\text{Al}_2(\text{SO}_4)_3 \cdot 14\text{H}_2\text{O}$), can reduce concentrations of some materials in runoff from sites treated with organic amendments (Edwards et al., 1999).

Sanudo-Wilhelmy and Gill (1999) examined dissolved ($< 0.45 \mu\text{m}$) trace metals and phosphate concentrations in surface waters collected along the Hudson River estuary, New York, between 1995 and 1997 and compared them with samples collected in the mid-1970s. They concluded that the release of Pb and Hg from watershed soils, and Ni and Cu from estuarine sediments, may represent the primary contemporary sources of these metals to the estuary.

Concentrations of copper (Cu), zinc (Zn), lead (Pb), cadmium (Cd) and nickel (Ni) measured in the headwaters of the Hawkesbury-Nepean River, Aust. were amongst the lowest reported in the literature for freshwater systems, and will be used as a benchmark for assessing the effects of increasing urbanization in the catchment (Markich and Brown, 1998). Davis et al. (1998a) studied the levels of chloride and bromide and the ratio between them in the groundwater of Yucca Mountain, Nev. Atmospheric precipitation generally has a mass ratio between 50 and 150 and summer runoff in urban streets, between 10 and 100. Samples of mercury (Hg) and methyl-mercury (MMHg) were collected during baseflow and storm flow from the Anacostia River, an urban, impacted river of greater Washington, D.C. (Mason and Sullivan, 1998). Total concentrations of Hg during the storm flow measured 3—5 times that of the baseflow indicating storm flow is the major vector for Hg in the Anacostia.

Birch *et al.* (1997) reported that point sources (waste dumps, sewage overflows, and discharge from a polluted river) were responsible for elevating sediment heavy-metal concentrations up to 50 times above background while NPS contributed in raising baseline levels to four times background. High trace-element concentrations in the Piedmont province streambed sediments were related to land use (O'Brien, 1997).

Solo-Gabriele and Perkins (1997) quantified metal transport (i.e. Fe, Cu, chromium [Cr] and arsenic [As]) for the Aberjona-River watershed and proposed storm-sewer overflows and direct urban stormwater runoff as mechanisms of metal transport. The runoff from roofs and streets contributed 50% — 80% of heavy metals, i.e., Cd, Cu, Pb and Zn, to the total mass flow in domestic wastewater (Boller 1997).

Schueler (1996b) summarized the effort to characterize metal and organic toxicants in stormwater discharges in the 700 mi^2 Santa Clara Valley, CA watershed. The highest Zn, Cd, Ni (nickel), Pb, and Cu concentrations were associated with industrial-land uses and all of the heavy industrial-area samples were found to be extremely toxic; probably from the dissolved metal fractions. Pesticides and other nonpolar hydrocarbons were probably responsible for the moderate to toxic samples obtained from the mixed-land-use areas.

Cadmium. van Geen and Luoma (1999) conducted a five-year study of dissolved Cd in San Francisco Bay, California and adjacent coastal waters. They showed that the composition of surface waters towards the mouth of the estuary was determined largely by the effect of coastal upwelling. However, surface samples collected throughout San Francisco Bay confirmed an internal Cd source unrelated to river discharge. The Cd content of a benthic foraminifer (*Elphidiella hannai*) in a dated sediment core from San Francisco Bay was measured to determine if the water column Cd enrichments in San Francisco Bay could be related to the rapid development of the watershed.

Copper. Copper mine spoil from Touro, A Coruna, Sp. was used in the construction of rural roads and tracks in the surrounding area. Roadside soils, sediment in drainage ditches, and water from first-order streams were analyzed to determine both total Cu content and the Cu fraction susceptible to uptake by plants. Despite some high soil concentrations of total Cu, Cu fraction susceptible to uptake was low in most samples, and no water samples were found to exceed European Community legislation thresholds for drinking water and for supporting fish (Arias et al., 1998).

Lead. Davis and Burns (1999) examined lead concentrations in runoff from painted surfaces. In many tests, high lead concentrations were found (using 100 mL of wash water over 1600 cm^2 of surface). Lead concentrations from 169 different structures followed the following order (median concentrations in the wash water): wood (49 $\mu\text{g/L}$) > brick (16 $\mu\text{g/L}$) > block (8.0 $\mu\text{g/L}$). Lead concentration depended strongly on paint age and condition, with the lead levels from washes of older paints being much higher than from freshly painted surfaces. Lead from surface washes were found to be 70%, or greater, in particulate lead form, suggesting the release of lead pigments from the weathered paints.

Mercury. Bonzongo et al. (1999) studied the impacts of land use and physicochemical settings on methyl mercury levels in the Mobile-Alabama River system. In the Coastal Plain portion of the state, Hg concentrations above the FDA's safe limit have been found in tissues of some fish species in both Fish River and Mobile Bay, Alabama. These rivers/streams receive most of their Hg from NPS (e.g. atmospheric deposition and inputs related to land use within the watersheds). They reported results of detailed investigations aimed to study the biogeochemistry of Hg and other trace metals, specifically the impact of different land-use types within the watersheds on Hg speciation. Glass and Sorensen (1999) examined a six-year trend (1990-1995) of wet mercury deposition in the Upper Midwest of the United States. The annual wet mercury deposition averaged $7.4 \mu\text{g Hg/m}^2\text{-yr}$ and showed significant variations between sites and illustrated significant increasing trends over the monitoring period. Warm (rain) season wet mercury deposition was found to average 77% of total annual wet deposition.

Platinum. Schaefer et al. (1999) studied the increasing concentrations of Pt, Rh, and Pd in urban areas associated with increased use of catalytic converters on automobiles. At a typical urban site, the daily deposition rate of Pt in airborne dust was up to 23 ng/m^2 .

Organic toxicants

Ashley and Baker (1999) developed inventories and identified sources for hydrophobic organic contaminants (HOC) in the surficial sediments of Baltimore Harbor, Maryland. There was enormous spatial variability in the concentrations of HOC at the 80 sampling sites which was not well correlated to grain size or organic carbon content, suggesting that nonequilibrium partitioning and/or proximity to sources were important factors. High concentrations of HOC were localized around major urban stormwater outfalls. Lower molecular weight PAH, having lower affinity for particles, may travel further from the sources. Ollivon et al. (1999) studied the PAH fluctuations in rivers near Paris (France). During storm events, the atmospheric contributions of PAH were negligible, compared to stormwater discharges. During heavy rains affecting the river Seine, high first flush PAH concentrations were observed, and about 25% of the PAH came from the rain and about 75% came from the stormwater. During light rains, atmospheric contributions only accounted for about 2% of the total PAH to the river.

Air-water exchange fluxes of 13 polycyclic aromatic hydrocarbons (PAH) were determined along a transect in the Patapsco River from the Inner Harbor of Baltimore, Maryland, to the mainstream of the northern Chesapeake Bay. The direction and magnitude of the daily fluxes of individual PAH were strongly influenced by the wind speed and direction, by the air temperature, and by the highly variable PAH concentrations in the gas and dissolved phases. The largest PAH volatilization fluxes occurred adjacent to the stormwater discharges, driven by elevated dissolved PAH concentrations in surface waters (Bamford, 1999).

Urban runoff samples were collected in a 1- year period in the Santa Monica Bay Watershed during both dry and storm periods and analyzed for polychlorinated dioxins, polychlorinated furans, and polychlorinated naphthalenes (Fisher et al., 1999).

A study of methyl tert-butyl ether (MTBE) in an alpine lake in the Sierra Nevada, Calif. suggested that neither highway runoff nor snowmelt runoff is a significant source of MTBE to the lake. Most MTBE is introduced to the lake from motorized watercraft operating on the lake during the summer (Reuter et al, 1998). Hydrocarbon pollution in lake core sediments, streambed sediments, stormwater and street surface sediments were investigated in the Brunette River watershed in Burnaby, British Columbia, Can. Hydrocarbon concentrations in streambed sediments corresponded to the land use indices of impermeable area and traffic density and road washoff of nonparticulate oil appeared to be an important source of hydrocarbons to stormwater solids, and ultimately streambed and lake core sediments (Larkin and Hall 1998). A thorough review of previous studies analyzing the contribution of highway runoff and urban stormwater to source loadings of semivolatile organic compounds (SVOC) and volatile organic compounds (VOC) showed that SVOC, primarily PAH, have been extensively studied, and are correlated with SS concentration. VOC have been studied to a lesser extent, and result primarily from urban land surfaces, but also from atmospheric washout (Lopes and Dionne, 1998). PCB found in street dust in Buffalo, N.Y. were redistributed by natural and vehicle-generated wind. More frequent street cleaning was suggested to reduce CSO and stormwater contamination of the Buffalo River (Irvine and Loganathan, 1998).

While spills may not be important in terms of the average annual loading of petroleum hydrocarbons in a watershed, large and medium size spills pose a significant risk to the aquatic resources in urban areas (Zandbergen and Hall, 1998).

Particle scavenging was the dominant contributor of PCB and PAH to falling snow in Minn., but less important in rain (Franz and Eisenreich, 1998). Gas scavenging was important only for low molecular weight PCB congeners and PAH which exceeded levels as predicted by Henry's Law constants for both snow and rain.

The concentration levels of phenol found in Terre Haute, Indiana were high enough to cause eye irritation and skin disorders in humans according to the U.S. Environmental Protection Agency (U.S. EPA) standards. The Environment Protection Department of Hong Kong identified stormwater as one of the likely sources of pollutants to Victoria Harbor, Hong Kong. Chlorohydrocarbons; PCB (as Aroclor 1254); total 2,2-bis (p-chlorophenyl)-1,1,1-trichloroethane (DDT); and total hexachlorocyclohexane (HCH) pose a significant risk, and probably have caused damage to the marine ecosystem as well as posing a hazard to seafood consumers (Connell *et al.*, 1998). Enhanced concentrations of dissolved methane (CH_4) and nitrous oxide (N_2O) were observed only in the western Oder Estuary of the Baltic Sea near the mouth of the Peene River. The distributions of CH_4 and N_2O in the investigated Bodden waters are, directly or indirectly, linked to the Peene River runoff (Bange *et al.*, 1998).

A receptor-source model was used to apportion source contributions for PAH in street and creek sediments. The model showed that vehicles along with the coke ovens, are the major contributors to PAH in street sediments (Sharma *et al.*, 1997). The spatial distribution and fingerprint patterns of PCB and polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/F) strongly indicated that CSO was a source of contamination in sediments near these outfalls. Evaluation of the industries operating within the CSO districts provides a link between tile facilities that discharge wastes to the combined sewer system (CSS) and PCB and PCDD/F found in the sediments (Huntley *et al.*, 1997). Concentrations of 18 hydrophobic chlorinated-organic compounds in streambed sediments from 100 sites throughout New Jersey were examined (Stackleberg, 1997). The highest median normal concentrations were found in samples from the most heavily urbanized and populated areas, with the lowest concentrations in the least developed, most heavily forested areas.

Trihalomethane (THM) formation potential at different stations of the Kurose River and the contribution from point and NPS within the river basin were determined. THM precursors in the river could be attributed mainly to industrial effluents, domestic wastewater, and agricultural drains with stormwater runoff contributing significant amounts of THM precursors to the river during storm events (Galapate *et al.*, 1997).

The source and fate of benzothiazoles leached from crumb rubber material (CRM) and asphalt containing 1% — 3% CRM were investigated (Reddy and Quinn, 1997). The environmental chemistry suggests that benzothiazoles from CRM should not be harmful. Measurements of aliphatic hydrocarbons in the Point Loma Wastewater Treatment Plant (PLWTP) effluents were mainly petroleum derived and were generally consistent with those of PAH. (Tran *et al.*, 1997). The PLWTP discharged approximately 3.85 metric tons of n-alkanes (C-10 — C-35) in 1994, well below the level (136 metric tons) estimated in 1979.

Steuer *et al.* (1996) reported on a two-year study that monitored stormwater from eight cities in the Lake Superior basin. Four to five storms were sampled at each station, for a broad list of conventional and toxic- substance-pollutant parameters, with fluoranthene and pyrene having the highest concentrations for any of the organic toxicants (site-median concentrations were about 5 $\mu\text{g/L}$).

Results reported by Shepp (1996) suggested that storm-runoff concentrations of petroleum hydrocarbons from automotive-intensive land uses typically range from 0.7-6.6 mg/L . Evaluation of these observations and their respective catchments suggested that the degree of automotive exposure (a combination of duration of exposure and volume of exposure) is the primary factor in the generation of petroleum hydrocarbons in storm runoff from automotive-intensive land uses. Delzer *et al.*, (1996) reported that in the most comprehensive evaluation of stormwater volatile organic compounds (VOCs) ever conducted, the USGS analyzed 592 stormwater samples collected from 16 United States cities for 62 VOC compounds, including methyl tert-butyl ether (MTBE). Stormwater was thought to be a potential source of MTBE in urban groundwaters. Four of the VOCs were detected in more than 10% of the samples (toluene, xylene, chloroform, and trimethylbenzene); MTBE was found in about 7% of the samples at a median concentration of 1.5 $\mu\text{g/L}$.

Revitt *et al.* (1996) identified the sources of hydrocarbons in urban storm runoff through an extensive monitoring program and the use of principal component statistical analyses. It was found that anthropogenic organics were invariably associated with the greatest concentrations of hydrocarbons in aquatic organism tissue. Automobile-exhaust-related hydrocarbons (especially fluoranthene and pyrene) and lubricating oil components (methylated homologues), along with biogenic hydrocarbons (high-molecular-weight odd-numbered carbon-chain alkanes, with $>\text{C}_{25}$) were most closely related

to bioassay-mortality rates.

Using site-specific nonpoint and point source PAH-concentration data from waterborne sources, PAH loadings in the near-shore regions of Massachusetts Bay were estimated to be 1.4×10^4 kg/yr (Cura and Studer, 1996). The greatest loadings of low-molecular-weight and total-PAH compounds were from POTW while the greatest sources of high-molecular-weight and carcinogenic compounds were nonpoint sources including rivers. Urban stormwaters and CSOs were found to have the highest PAH concentrations of the various source types.

Pesticides and herbicides. Lee et al. (2000) found that stormwater runoff in San Diego Creek was toxic to *Ceriodaphnia* and *Mysidopsis*. About half of this toxicity was found to be attributable to the use of the organophosphate pesticides diazinon and chlorpyrifos used in the urban areas for structural termite and ant control and for lawn and garden pest control. Lutes et al. (2000) investigated an eleven-acre lake on a golf course at NAS Jacksonville in terms of potential ecological and health risks posed by sediments and fish in the lake. The identified contaminants of interest at the site; PCBs in fish, metals in sediments, pesticides in sediments, and PAHs in sediments, are most likely attributable to storm water impacts. The identified exposure pathways to the contaminants are through recreational fishing and the use of the lake by wildlife.

Temporal trends of three phenoxyacid herbicides: 2, 4-D, dichlorprop and MCPA and the phenolic herbicide (bromoxynil), were determined in ambient air and precipitation over a 4-yr period within a well-defined watershed in southern Manitoba. Elevated levels of these herbicides in creek water samples were observed during period of high concentration in both atmospheric compartments, despite the lack of surface runoff events within the watershed over that period (Rawn et al., 1999).

Farrugia et al. (1999) studied household herbicide use. They found that typical urban uses of herbicides exceeded agricultural uses, and the transfer coefficients (amount of the herbicide in the runoff compared to the amount applied) was also higher in urban areas. The highest measured diuron concentration was 20 µg/L, while the average was 5 µg/L. Compared to EEC standards for drinking water protection (0.1 µg/L), they concluded that suburban uses of herbicides may severely endanger drinking water supplies.

A study that examined surface waters adjacent to golf courses in N.C. showed that levels of pesticides and nutrients were generally below U.S. EPA health advisory levels in water bodies on the course, and always below detection levels at the outflows from the courses (Ryals et al., 1998). An analysis of water samples from 64 rivers and streams in New York showed that pesticide concentrations were dependent on upstream land use and pesticide application patterns (Phillips et al., 1998). Specific pesticides are correlated with each land use type.

Pesticides present in rainwater do not pose a greater groundwater contamination problem during artificial roof runoff infiltration (a practice in Switz. to reduce runoff) than does the direct application in agriculture (Bucheli et al., 1998a); however, the herbicide (R,S)-mecoprop, a root protection agent in Preventol B 2 commonly applied to roofs, is of the same order of magnitude as loads from agricultural applications (Bucheli et al., 1998b).

Monitoring and Sampling

Dwyer and Wissing (2000) described Waterwatch Australia, a national monitoring and environmental education program. The program has involved over 2000 groups monitoring approximately 5400 sites in 246 catchments, with most work done by volunteers and community groups.

Buried mineral soil-bags and natural solutions, studied as indicators of forest response to elevated N and S inputs at the BBWM, were reported by Fernandez et al. (1999) having continued utility in environmental monitoring and assessment research. In the Mediterranean region, climatological factors make CSO a major urban pollution problem that should be monitored and controlled. In comparing rainfall estimates from weather radar pictures to a rain-gauge network in terms of the ability to predict sewer flow in the urban basin in Barcelona, Spain, the results showed that the use of radar data enabled the combined sewer system model to improve the reproduction of the observed flows. Also indicating the spatial description of rainfall was a key problem in modeling the events giving rise to CSO (Sempre-Torres et al., 1999).

A receiving water quality monitoring program was developed to measure beneficial use impacts resulting from toxicity in stormwater runoff. The goals of the water quality monitoring program were to determine the persistence, fate and

significance of the aquatic toxicity in the receiving water (Taylor, 1999).

Gracie (1999) presents a monitoring protocol and evaluates performance of several projects which have had varying degrees of success. Clar et al. (1999) described the current approach adopted by Baltimore County, Maryland to integrate stream stability assessment and water quality modeling for a comprehensive study of the Patapsco River Watershed in south-western Baltimore County.

The 1996 handbook *Environmental Indicators to Assess Stormwater Control Programs and Practices* described the use of 26 indicators within 6 general categories B water quality, physical/hydrological, biological, social, programmatic and site-specific B to measure the success of stormwater programs. The handbook also suggests a methodology for using the indicators to identify problems within local watersheds and for assessing, re-evaluating and improving stormwater management programs. With grant assistance from the Water Environment Research Foundation, the Santa Clara Valley Urban Runoff Pollution Prevention Program (SCVURPPP) was demonstrating this methodology at a watershed scale (Coyote Creek watershed, Santa Clara County, California) and at a smaller, more defined scale, that of a 28-acre industrial catchment in the City of Santa Clara, California (Cloak and Bicknell, 1999).

A new settling testing method was compared to a traditional test in a laboratory side-by-side evaluation. The comparison attempted to determine whether these tests can capture the rapidly settling particles in wet-weather flow. A summary of the performance, as measured by predicted percent removal of the columns for 15 laboratory bench-scale tests, and the limitations and advantages of each approach were presented and compared (O'Connor et al., 1999). Kuo et al. (1999) presented results of field tests of pollutant removal efficiencies of grassed swales conducted in Taiwan and Virginia. The Virginia experiments tested a highway median swale, while the Taiwan experiments were conducted on an agricultural test farm.

The specific goals of the Small Business Innovation Research (SBIR) project, sponsored by the Federal Highway Administration (FHWA), was to develop a small, inexpensive, simple, effective sheetflow sampler to aid transportation officials in meeting their regulatory requirements. The field testing program includes the installation of approximately 18 samplers throughout varying highway environments in Virginia, Maryland, and California. Stormwater samples will be collected and analyzed for various highway pollutants over a period of 9 months (Graziano et al., 1999).

According to Klove and Bengtsson (1999) the hydrology of a cutover fen was studied from May to October in 1995 and 1996. Rainfall equivalent depths were measured every 15 min and stream runoff was continuously monitored. Storm runoff was separated into different components; rain falling directly into channels and rapid groundwater response based on a contributing area method and on different electrical conductivities of rain-, ground- and stream-water. The Ohio Environmental Protection Agency employed biological, chemical, and physical monitoring and assessment techniques to assess how effectively they were achieving their goals of the Clean Water Act, namely the maintenance and restoration of biological integrity and the basic intent of water quality standards (Yonder et al., 1999). Strecker (1999) described some of the problems with typical BMP monitoring and effectiveness reporting; and suggested the utilization of consistent stormwater monitoring techniques.

A method for quick, simple, and inexpensive analysis of CSO used a statistical approach for rainfall analysis and considered the preceding dry period, which has a significant affect on the pollutant loading of the overflow (Udale and Osborne, 1997). The Greater Houston Wastewater Program devised an innovative flow-remonitoring effort that allowed engineers to eliminate the construction of overflow-control facilities. The initiative integrated temporary- and permanent-meter-flow data that allowed for modifications in design to save 77-million dollars (Bagstad, 1997). MacDonald and Phillips (1997) discussed applications and configurations for multiple-path ultrasonic transit-time flowmeters under various hydraulic regimes commonly encountered in wastewater collection systems. A station was established to perform continuous high quality time-series flow, wastewater, and stormwater-runoff characteristics monitoring. Time-series research will be carried out in order to establish knowledge of dry-weather characteristics and rainfall-runoff relationships including the variability of relevant stormwater pollutants (Schaarup-Jensen *et al.*, 1997). An experimental urban catchment was created in the center of Paris for the purpose of obtaining a description of the pollution of urban WWF. Results revealed that a significant portion of pollution originates from inside the combined sewer and it is suspected that the pollution is probably due to resuspension of sewer sediments (Gromaire-Mertz *et al.*, 1997). Baloch (1997) observed large seasonal differences in river-mercury (Hg) concentrations and loadings showing dramatic increases in response to spring snowmelt and precipitation events. Results revealed total Hg concentrations were highly correlated with SS.

Dowling and Mar (1996) developed and tested a low-cost “culvert composite sampler” for obtaining flow-weighted stormwater samples. This sampler should enable much more cost-effective stormwater sampling for many purposes, including NPDES monitoring. Initial testing was performed for a sheetflow sampler to collect highway runoff using an acrylic prototype (Stein et al., 1998).

Lee and Jones-Lee (1996) stressed the need to focus receiving-water stormwater-monitoring activities on those pollutants causing the specific problems identified, instead of using very broad (and expensive) monitoring approaches. Highly focused site-specific studies are needed for each type of use impairment. The focus of the monitoring program should be devoted towards the suspected use impairments, such as, aquatic-life toxicity and bioaccumulation, closure of beaches and shellfish harvesting due to high bacteria concentrations, etc. When specific impairments are identified, then detailed chemical analyses may be justified in order to identify the specific compounds causing the observed problems.

Fuchs *et al.* (1996) investigated the use of biofilm samplers (six glass plates inside a 30 cm PVC pipe, initially coated with stearic acid and exposed for 14 days) to indicate heavy-metal variations in an urban area. The biofilm samplers were found to be very representative of more difficult to conduct sampling efforts, and are probably more representative of conditions affecting aquatic life.

Rainfall and Flow Measurement

Chao and Hegwald (2000) documented procedures for deploying flow meters and for data evaluation to ensure that a flow-monitoring program would be successful. Stonehouse et al. (2000) reported on the work of the Flow Metering Task Force (FMTF) in Detroit, whose purpose was to evaluate and improve the current flow metering occurring in the Detroit sewer system. The guidelines developed by this group included procedures for meter evaluation, data collection and review, and information sharing. This group also developed a dye dilution testing protocol that provided more accurate results than prior protocols. A specialized probe using time-domain reflectometry (TDR) was developed, calibrated and field tested for continuously measuring soil-water content and surface runoff during studies of water erosion and sediment transport (Thomsen et al. 2000). The laboratory investigation of this TDR probe showed that water levels could be measured with a standard deviation of less than 2 mm. Zandbergen and Schreier (2000) investigated the current methodologies used to assess the impervious cover in a watershed. These included ground surveys, stereo-photogrammetry, air photo interpretation, and satellite image analysis. The following factors were found to influence the accuracy of imperviousness measurements (in order of decreasing importance): selection of imperviousness factors; accuracy and scale of land use mapping; consideration of land cover in addition to land use; and watershed delineation.

Burrows et al. (1999) evaluated a flow stick with inclination transducer. The data from the flow stick, when combined with a depth measure, provided an accurate measure of the instantaneous flow rate in a storm, sanitary or combined sewer. Goyen and O’Loughlin (1999) described their project in which they used intra-catchment gauging stations in Canberra, Australia to collect data regarding rainfall and runoff. They determined that the spatial and temporal variability of rainfall and runoff even over a single catchment were great enough to ensure the single-parameter models cannot perform well consistently and so, they proposed a runoff simulation model that incorporates the intra-catchment elements needed to determine runoff from a larger watershed. Tilley et al. (1999) demonstrated the inadequacy of current stream-gauge height-measurement-averaging techniques combined with a rating curve to estimate flow at a site during flash flooding in urban areas. They recommended that the monitored gauge height be used for each subarea for each time increment in order to calculate the volume of flow during a flash flood. Steiner et al. (1999) demonstrated the necessity for having good quality rain gauge data if it will be used to adjust for biases in radar rainfall estimates of precipitation. They concluded that the differences resulting from radar data processing scenarios were small compared to the effects of rainfall data adjustment based on rain gauge information. Maheepala and Perera (1999) described the quality assurance checks program used during the collection of urban drainage hydrologic information for a flood-prediction model for Victoria, Australia. They discussed not on the quality of the data but also the occupational safety and health aspects of collecting it. Guitierrez (1999) reported on the development of regional regression equations for predicting flows at ungaged urban catchments in Mexico.

Riotte and Chabaux (1999) found that the ratio of U-234/U-238 could be used to investigate hydrological processes such as flooding events. Weiler et al. (1999) used natural tracers/isotopes with mass balance calculations to determine the fraction of surface flow and subsurface flow in the receiving water prior to a rain event. The isotopes were also used to demonstrate the importance of infiltration water to the quantity of subsurface runoff due to preferential flow. McDonnell et al. (1999) combined tracer studies (using ^{18}O) with measures of rainfall and runoff in four nested catchments on South

Island, New Zealand. The results showed that water contributions from various source areas in a catchment was a complex function of the mixing of these contributions and of the contact time in the groundwater and drainage system. Mehlhorn and Liebundut (1999) determined that the modeling approaches for tracer hydrology and rainfall-runoff modeling were mathematically equivalent and therefore, tracer time parameters could be used to calibrate baseflow runoff models. Coupling the water age and turnover time of the mobile groundwater led to a more accurate determination of the baseflow in the stream.

Post et al. (1999) used hand-held radiometers to evaluate the ground cover of semiarid rangelands and to correlate the data collected with the hydrologic characteristics of the area. The results showed that vegetative cover and percent runoff were highly correlated with spectral reflectance, while soil-rock cover and eroded sediment were poorly correlated with the reflectance.

A method to adjust the daily precipitation measured by the U.S. National Weather Service (NWS) 20.3 cm (8 in.) standard gauge for wind-induced undercatch, wetting loss, and trace amount of precipitation was tested at ten climate stations in Alaska during 1982-83. Results showed that daily adjustment increased the gauge-measured annual precipitation by up to 800 mm for the two years (Yang et al., 1998). An accuracy test conducted in the Stephen F. Austin Experimental Forest, Tex. revealed that a U.S. standard gauge, weighing-type recording gauge, a standard gauge fitted with an Alter windshield, and a pit gauge showed each gauge to have an average deficiency greater than 10% when compared to a recording anemometer (Chang and Flannery, 1998). Correction for wind effect on angle of raindrop reduced the deficiency from 11% to 6% leaving the remaining error to wind effects, nonrandom errors and other unknown sources. The procedures were presented for the collection and quality control of rain data from a network of tipping bucket rain gauges in Den. carried out by the Danish Meteorological Institute as input to software packages such as MOUSE and SAMBA for designing sewers and storage basins, and simulating overflows and flooding. Although it is possible to improve the efficiency of the quality control, long term corrections will always be necessary (Jorgensen et al., 1998).

Spatial and temporal variability in rainfall concentrations of several contaminants were monitored at seven locations in or near the Conodoguinet Creek watershed of south-central Pa. and compared precipitation quality in forested, agricultural and urban areas. The major ion concentrations were related more to regional influences than local while herbicides in precipitation may have had more local influences (Shertzer et al, 1998). Quality checks also indicated that trained volunteers were reliable in collecting data in a timely manner. The Residential Stormwater Monitoring Project, initiated by the Boston Water and Sewer Commission in March of 1997, characterized the seasonal variation in the quality of stormwater discharged from a low density residential area (Schofield and Eggleston, 1998). The project included precipitation monitoring, stormwater quality sampling and quantification of flows at a single manhole location for up to five storms per season for a period of one year, surface stormwater quality sampling at five gutter locations, and inspection and sampling of dry weather flows in storm drains.

Short-term flow monitoring programs such as those employed for SSO and CSO should focus on the anticipated use of collected data (Hollenbeck, 1998). Monitoring should start approximately two weeks prior to initiation of the normal "storm season" and a minimum of 90 days (ideally 120) of short-term monitoring are necessary to determine a reliable relationship between rainfall intensity and stormwater inflow. Flow monitoring devices at or upstream of sewer overflow structures for recurrent CSO and SSO in the Pittsburgh, Pa. were installed to determine the quantity of sewage which pass through selected regions. The monitors collected data until the selected study points stayed within specified limits for eight consecutive months (Patsey, 1998). In a Boston, Mass. sewer separation project, several flow meters recorded depths which differed significantly from wet and dry weather manual measurements. Analysis determined that the meters were most likely reading a constant fraction of the actual change in depth (DePasquale and Caulfield, 1998).

The U.S National Weather Service radar images have produced significantly greater resolution in the spatial distribution of rainfall in comparison to raingauges alone which can contribute to the accuracy of CSO modeling (Burgess *et al.*, 1997).

Toxicity Testing

Baker et al. (2000) reviewed a project undertaken as part of Mecklenberg County's Surface Water Improvement and Management (SWIM) program, and which included restoration in the highly-urbanized Edwards Branch watershed. The project emphasized the importance of using a variety of monitoring techniques - EPA stream habitat assessment protocol, ambient water quality monitoring, fish and benthic macroinvertebrate surveys, and channel cross-section monitoring - to

investigate the effectiveness of the installed BMPs and other restoration techniques. The bioassessment approach used in the Camp Creek Watershed in Fulton County, Georgia was reviewed by Jones (2000a). By linking the biological results with the water quality monitoring data, management goals were set and improvements were focused on critical management areas. The paper by Rochfort et al. (2000) encouraged the use of benthic assessment techniques, in conjunction with toxicity testing and sediment and water chemistry analyses, to determine the impacts of stormwater and combined sewer overflows (CSOs) on receiving water and the biota. The results from all three analysis techniques showed that the sediment chemistry could not be correlated to either the toxicity testing or the benthic community impacts, and that a combination of techniques was necessary to show a complete picture of stream health.

Chappie and Burton (2000) described the application of in-situ aquatic sediment toxicity testing for stormwater runoff assessment. Burton et al. (2000) described the problems associated with using traditional toxicity testing methods for assessing the biological impacts of stormwater runoff. The problems noted include the inability to produce reliable conclusions when this technique was used to detect the adverse effects of fluctuating stressor exposures, nutrients, suspended solids, temperature, UV light, flow, mutagenicity, carcinogenicity, teratogenicity, endocrine disruption, or other important subcellular responses. In watersheds receiving multiple sources of stressors, accurate assessments should use a range of laboratory (such as whole effluent toxicity [WET] tests) and novel in situ toxicity and bioaccumulation assays, and should include a simultaneous characterizations of physicochemical conditions and indigenous communities. de Vlaming et al. (2000) used USEPA protocols for freshwater toxicity testing to evaluate ambient water quality in California. Testing since 1986 showed that the three WET tests, when performed along with toxicity identification evaluations (TIEs) and chemical analyses, were useful in identifying pollutant sources and identifying potential benefits of alternate land uses or best management practices. Tobiasson and Logan (2000) reported on the benefits of using WET testing of stormwater at outfalls to trace sources of pollution at Sea-Tac International Airport. WET testing was found to be very effective in helping to identify a zinc-galvanized metal rooftop as the source of zinc contamination and therefore the source of the toxicity of the stormwater runoff. Ellis (2000a) reviewed using in-situ biomarker techniques to evaluate the effects of transient pollution events, such as the inflow of stormwater runoff, in urban receiving waters. This paper also discussed the limitations of more traditional toxicity tests such as the Direct Toxicity Assessment (DTA) procedures for assessing transient events that leave sub-lethal stresses on the biota.

Several field and laboratory assays were employed below an urban storm sewer outfall to define the relationship between stormwater runoff and contaminant effects. Specifically, two bioassays that measure feeding rate as a toxicological endpoint were employed in the field and in the laboratory, along with bioassays measuring survival and growth of test organisms. The results of the study suggest significant toxicity at this site was due to accumulation of contaminants in the sediment and the mobilization of these contaminants during a storm event (Hatch and Burton, 1999).

Doherty et al. (1999) compared *Ceriodaphnia dubia* and the Microtox® inhibition tests with *Vibrio fischeri* on industrial and municipal wastewaters. For samples that were not toxic, the Microtox® method correlated well with the results with the *C. dubia* results. However, for samples that were toxic to *C. dubia* after 24 hours, the Microtox® detected toxicity in only two. For five other samples that the Microtox® found to be toxic, the *C. dubia* required a minimum of 48 hours of exposure before toxicity could be detected. Kosmala et al. (1999) used *C. dubia* in laboratory toxicity tests in combined with field analysis of the *Hydropsychid* life cycle to assess the impact of both the wastewater treatment plant effluent and the stormwater overflow on the receiving water. They found that the results seen in the laboratory toxicity tests and in the in-situ biological measurements were due to nutrient and micropollutant loadings. Marsalek et al. (1999) used several different toxicity tests to assess the various types of toxicity in typical urban runoff and in runoff from a multi-lane highway. The tests included traditional toxicity analysis using *Daphnia magna*, the Microtox® toxicity test, sub-mitochondrial particles and the SOS Chromotest for genotoxicity. Tucker and Burton (1999) compared in-situ versus laboratory conditions for toxicity testing of nonpoint-source runoff. They found that NPS runoff from urban areas was more toxic to the organisms in the laboratory while the agricultural runoff was more toxic to the organisms exposed in situ. The differences seen between the two types of toxicity tests demonstrated the importance of in-situ assays in assessing the effects of NPS runoff.

Brent and Herricks (1999) proposed a testing protocol for the toxicity assessment of wet weather events that includes an event-focused toxicity test method, a corresponding test metric that more accurately represents the toxicity of brief exposures, and an event-based index that described the acute toxicity of wet weather events. This testing protocol was designed to quantify toxic response produced by brief contaminant exposures (< 24 h), as well as time-varying contaminant exposures, which were typical of wet weather events. The protocol described the use of an event-focused toxicity test to determine a PELET50 (post-exposure lethal exposure time for 50% of the population) metric for individual

event samples.

When considering urban runoff toxicity, it was necessary to carefully consider magnitude, duration, and frequency in any toxicity analysis. First, to measure this toxicity it was necessary to apply a new paradigm, the time-scale toxicity paradigm. The time-scale toxicity paradigm was reviewed, and data from storm events was provided to illustrate paradigm utility in assessing the toxicity of urban runoff and the related impact of urban runoff on receiving systems (Herricks, 1999).

Researchers in King County, Wash. used transplanted and wild mussels to monitor Cu, tributyltin and PCB. In the wet season, concentrations of Cu increased in wild mussels near CSO although the source of Cu was unclear (Munger et al., 1998b). Seidl et al. (1998a) found that CSO contributed toxicity to the River Seine, Fr. even after settleable solids were removed and effluent was diluted five-fold. The results of this study suggest that Zn may contribute significantly to phytoplankton toxicity of CSO effluent. A further CSO study in the Seine comparing biodegradable to residual dissolved organic carbon (BDOC to RDOC) showed that an additional source of carbon was contributing to the oxygen budget, possibly phytoplankton or degraded particulate organic matter (Seidl et al., 1998b). In Paris, Fr. further CSO studies showed a higher proportion of refractory organic carbon during rain events than during dry weather with a possible contribution of the in-sewer sediments to the bacterial wet weather flux (Seidl et al., 1998c). A multi-parameter continuous water quality monitor was examined for evaluating in-situ photosynthesis/respiration rates of microbes (Easton et al., 1998). The city of Indianapolis, Indiana completed a large instream sampling program directed at characterizing ambient bacteria levels in the White River and its tributaries. Analysis showed less wet weather influence on bacteria in the White River than in the tributaries (Burgess et al., 1998). Søballe (1998) illustrated the difficulties inherent in monitoring an ecosystem. Monitoring programs provide unbiased evaluation only for those phenomena whose temporal and spatial characteristics match those of the monitoring program.

Two years of sampling in San Francisco, Calif. revealed that only certain individual dioxins/furans and PAH were commonly detected in the city's collection system, and may be indicative of specific sources. PAH were also detected more frequently in catchbasin influent than effluent implying that particle deposition in catchbasins may be an effective removal mechanism for PAH (Moore et al., 1998b).

Testing for Chemical Pollution and Pollution Tracers

Hartmann et al. (2000) investigated the usefulness of linear alkylbenzenes (LABs), a byproduct of LAS detergents, as a marker of sewage in the marine environment. Their usefulness was confirmed in Narragansett Bay where LABs were found in higher concentrations near the urban outfalls and in the upper layers of the sediment. Standley et al. (2000) investigated the potential for using molecular tracers of organic matter, such as fecal steroids, caffeine, consumer product fragrance materials, and petroleum and combustion byproducts to trace sources of organic matter in a watershed. The authors showed that molecular tracer content could be correlated with watershed-scale land uses and that wastewater treatment plant effluents were associated with caffeine and fragrance materials while urban runoff was associated with the PAHs. Allison et al. (2000) described two years of monitoring and characterization (litter material larger than 5 mm) of freeway runoff in California.

Maldonado et al. (1999) evaluated the use of trialkylamines and coprostanol as chemical tracers of pollution in the western Mediterranean and the northwestern Black Sea from urban areas. Trialkylamines were found to be the better marker of urban pollution in the water because they had higher concentrations in the water and were not as likely to associate with the particulate phases. Sidle and Lee (1999) used the deuterium isotope to determine the origin of the stormwater runoff from an urban watershed. Deuterium isotope concentrations were significantly different in the vadose and saturated zones between an area affected by a storm sewer leak and an area where a stream contributes to the groundwater. The measurements were useful in modeling leaks and seepages and in improving mass balances in urban watersheds.

Soerens et al. (1999) reported on the development of a sampling scheme to find the minimum required sampling interval during a storm that would be necessary to obtain realistic pollutant loadings for TMDLs. They found that the optimum sampling interval was dependent on the parameter measured and the stream order. Persson et al. (1999) developed and demonstrated a passive in-situ sampler for metals in stormwater runoff. The results indicated that the metals concentration in the passive sampler corresponded to the bioavailable fraction of the metals in the runoff. They also found that in-situ deployment of the passive sampler with direct analysis of the water by laser ablation-ICP/MS provided better accuracy than traditional bottle sampling, either a grab or a composite sample.

Instream water quality monitoring assessed CSO in the Rouge River, Mich. (Hufnagel et al., 1998). The primary CSO impacts on the river were bacteria and oxygen demand while solids and nutrients were not identified as a limitation of river viability.

A field program sampled conventional parameters, i.e., bacteria, trace metals and organic compounds, in the water column, sediments, CSO discharges and fish and invertebrate tissues in the Duwamish River and Elliott Bay, Seattle, Wash. (Mickelson, et al., 1998). Because concentrations were too low for conventional sampling methods, semi-permeable membrane devices were used to assess water column organic concentrations and low level mercury sampling techniques were used to estimate mercury concentrations. In order to optimize the design and management of sewer networks and settling tanks, there is a need to determine the settling velocity characteristics of sewage and stormwater solids (Lucas-Aiguier et al., 1998). Several methods to determine the settling velocity characteristics of sewage and stormwater solids were selected and compared and results indicated that there is a need to develop an international test procedure in order to be able to compare the results uniformly.

Chemical transfer from soil to surface runoff was simulated using a gypsum tracer under dry, wet, and water-table conditions. During the dry testing, no tracer was found in the stormwater runoff and tracer concentrations were found to decrease exponentially with time under wet and water-table conditions (Zhang, 1997). Observations of rainstorm and sprinkling experiments were conducted to demonstrate stormwater runoff generation in colluvial soils is through near-surface bedrock (Montgomery *et al.*, 1997).

Biological and Microbiological Testing

Quintero-Betancourt and Rose (2000) investigated the potential use of stormwater and/or reclaimed water to rehydrate wetlands in St. Petersburg, Florida. The adequacy of using these waters was assessed through microbial water quality testing using bacterial indicators, coliphages, *Cryptosporidium* and *Giardia*. Long et al. (2000) evaluated the potential of using three alternative (compared to traditional coliform testing) source-specific indicator organisms for determining the human health risks associated with a water source and for determining if the source of the bacterial contamination was human or grazing animal. These alternative organisms were sorbitol-fermenting *Bifidobacteria*, *Rhodococcus coprophilus*, and serogroups of F+ coliphages), and they were found to correlate well with predictions of land use contributions to a receiving water. Rex (2000) reported on the impacts of changing from coliforms to *enterococcus* as the indicator organism of water quality. The paper advocated that more studies need to be done to improve the understanding of *enterococcus* behavior during treatment so that its use can provide information about the quality of CSO control. Brion and Mao (2000) researched the use of atypical colonies found in the total coliform test as a part of watershed monitoring. The ratio of atypical colonies to coliphage concentrations correlated well with the degree of known fecal pollution. Meek et al. (2000) advocated the use of shellfish as indicators of bacterial pollution of water. When compared to coliforms, the shellfish gave a better representation of the pollution levels and the changes over time of bacterial concentrations in the water. An evaluation of the naturally-forming algal community in stormwater detention ponds by Olding (2000) showed that this algal community could be used to demonstrate the effectiveness of the detention pond as a treatment device. The taxonomic breakdown of the community also indirectly showed the pond influent water quality.

Myrmel et al. (1999) presented their work on using adsorptive filtration and PCR to detect small round-structured viruses in water and wastewater. The method detected virus concentrations of 0.5 – 5 virus particles per milliliter in a 500-mL sample. Abbaszadegan et al. (1999) compared PCR to cell culture testing for the detection of viruses in groundwater. They found that, with the improved sample-processing technique and large-volume amplification protocol, the PCR test was a rapid and effective tool for screening water for enteroviruses, hepatitis A virus, and rotavirus. Betts (1999) reported on the evaluation of “DNA chip” technology for the rapid, sensitive and inexpensive testing of water for bacteria, parasites and viruses. Zisette et al. (1999) used a genetic fingerprinting technique to assist in identifying source of microbial contamination to Drayton Harbor Watershed, Washington. The results from the bacterial tests were then to be used to determine which sources (municipal sewage discharge, failing septic systems, animal management practices, seafood processor discharges, and people who live aboard houseboats at the marina) were causing the shutdown of the oyster and shellfish harvest areas. Clancy and Hansen (1999) discussed the lack of use of protozoan monitoring data in public health decision-making. They found in their survey that the primary reason cited by water companies was unreliable data. However, the protozoan data has been used successfully in conjunction with other water quality results to assess treatment efficiency and support investment planning.

Matlock et al. (1999) used the Matlock Periphytometer to measure nutrient limitations and trophic status in situ in the

Bosque River Watershed in Texas. The data was used to develop a lotic ecosystem trophic status index (LETSI), and through the use of LETSI, differences in nutrient limitations in tested streams were detected, including two streams which were co-limited by nitrogen and phosphorus. Toetz et al. (1999) related annual phosphorus loadings from eight subbasins in the Illinois River impacted by NPS runoff to the alkaline phosphatase activity (APA) in the water. The correlation between APA and soluble reactive phosphorus and between APA and the annual predicted phosphorus loading by the SIMPLE model allowed the researchers to demonstrate which of the eight subbasins did not require pollution abatement and were not in jeopardy of becoming eutrophied.

Fry (1999) measured the concentration of stable C and N isotopes in the clam *Potamocorbula amurensis* in San Francisco Bay. He determined that the carbon isotope concentrations in the clam correlated to the amount of riverine, freshwater, input into the Bay while the nitrogen isotope concentrations could be correlated to the watershed nutrient loadings due to human activity.

The cost and efficiency of different techniques for processing rapid-assessment samples of macroinvertebrates were evaluated by comparing the ability of data generated by each technique to discriminate between unpolluted reference sites and sites with mild to severe pollution from municipal effluent and urban stormwater runoff (Gowns *et al.*, 1997). Of three metrics tested, SIGNAL had the most highly significant differences between reference and polluted sites and was the most robust to variations in processing method.

Surface-Water Impacts

The impact of three demographic and cultural trends - global urbanization, “quality of life” emphasis, and a move towards flexible management - on technology and the regulatory system was discussed by Ruta (2000), especially given the fact that many thousands of U.S. waterbodies still do not meet water quality standards. One example of the watershed-view of impacts was the Urban Pollution Management (UPM) procedure described by Artina and Maglionico (2000). This procedure was developed in England to evaluate the impact on receiving waters of pollutants discharged from sewer overflows during rainfall events. Garland and Pfeffer (2000) proposed using a watershed-based approach to evaluate the impacts of runoff from contaminated sites at the Oak Ridge DOE Reservation and for determining the optimum location and type of pollution control measures. They documented that pollutants released from the contaminated sites typically are transported to the Clinch River through subsurface shallow flow to surface waters where, if they bind well to sediments, they accumulate in aquatic sediments. Otherwise, they are transported off-site via the Clinch River.

Bertrand-Krajewski et al. (2000) reviewed their Experimental Observatory for Urban Hydrology project that demonstrated the need for improved knowledge about the interactions between urbanization, pollutant discharges, impacts on the natural environment, and socio-economics. The aim of the project will be to improve methodologies for investigating the sustainability of urban water systems. Collins et al. (2000) reviewed the USEPA’s Clean Water Compliance Watch (CW2) Environmental Monitoring for Public Access and Community Tracking (EMPACT) project. EMPACT projects use state-of-the-art technology to track environmental conditions and to provide easy public access to information in easily-understood language.

Fernando et al. (2000) presented the development of effectiveness indicators (“a measurable feature that provides managerially and scientifically useful evidence of stormwater and ecosystem quality or reliable evidence of trends in stormwater quality and program effectiveness”) for stormwater and watershed management programs and the development of a regional monitoring program for the Hampton Roads Planning District Commission (Virginia). As reported by Schaad and Kam (2000), the City of Kelowna completed a State of the Environment Report which examined air, land and water quality. Thirteen of the twenty-two indicators directly addressed watershed health. These indicators were designed to show current watershed health and future trends. Cloak (2000) described the implementation of twenty of the Center for Watershed Protection’s Environmental Indicators to Assess Stormwater Programs and Practice, and showed that the indicators were most useful when organized into a framework that could be used to inform stakeholders and the public. The investigation (Cloak et al. 2000) separated the indicators into two groups: The first group, the programmatic indicators targeted at measuring specific program activities, was useful for documenting and understanding pollution-prevention efforts. The second group of indicators (application of physical, water-quality, and biological measurements at a watershed scale) were useful for an overall assessment of stream function and an understanding of the natural and anthropogenic factors influencing those functions.

Albert and Limbeck (2000) reported on the effects of urbanization on storm water quality in five New Jersey watersheds.

The report reviewed the water quality, instream habitat, benthic macroinvertebrates, and stream channel changes due to urban runoff. The work also examined various assessment methods to determine which of these methods could be used to develop non-point source or stormwater related goals and objectives.

McMahon and Cuffney (1999) described the U.S. Geological Survey's National Water Quality Assessment (NAWQA) Program which was intended to study the relationship between varying levels of urban landuse development in drainage basins and in-stream water quality, as measured by physical, chemical, and biological indicators. These studies were being conducted near Boston (Massachusetts), Salt Lake City (Utah), and Birmingham (Alabama), where rapid urbanization was occurring.

David et al. (1999) performed a study to determine the response of stream water dissolved organic carbon (DOC) and organic acidity to increased inputs of ammonium sulfate to a whole catchment. Several mechanisms exist, including evaporative concentration, vapor-liquid phase partitioning, lowered washout volumes of atmospheric deposition water, and dry deposition, which may lead to elevated concentrations of trifluoroacetic acid (TFA) in atmosphere and surface waters above levels expected from usual rainfall washout (Wujik et al., 1999). Correll et al. (1999) reported on a study to determine the relationships between precipitation at the seasonal and annual scale and water discharge per surface area for seven contiguous first and second-order tributaries of the Rhode River, a small tidal tributary to the Chesapeake Bay, Maryland.

Consistently, N and P concentrations increased as the proportion of land area used for dairy waste application fields. The proportion of total P (TP) in runoff represented by soluble reactive P (SRP) also increased as the percent of dairy waste application fields above a sampling site increased; stormwater runoff of nutrients from dairy waste application fields was indicated as the predominant source of NPS nutrients impacting surface water quality in the upper North Bosque River (UNBR) watershed (McFarland et al., 1999). Mason et al. (1999a) reported that the chemistry of a first-order stream in Amherst, Maine with a catchment area of 103 ha has been strongly altered as a result of road salt application at a rate of approximately 4 t of NaCl per year in the lower 15% of the catchment.

Pesticide compounds, relative to the landuse composition of the basin, were detected in all 50 water samples collected from streams in New Jersey and Long Island, New York, during June 9-18, 1997. Physical and chemical properties as well as application rates of the pesticides studied affect their detection frequencies. Although all pesticide concentrations were within both EPA and State maximum contaminant levels (MCL) and health advisory levels (HAL), these criteria apply only to individual compounds, and more than one compound was detected in 49 of the 50 samples collected (Reiser and O'Brien, 1999). Watershed properties such as peatland area have considerable promise as predictors for estimating total mercury (THg) transport in streams draining forested watersheds in the Great Lakes States (Kolka et al., 1999). Sixteen largely agricultural watersheds in the upper portion of the North Bosque River of central Texas were reported by McFarland and Hauck (1999). The proportion of total P (TP) in runoff represented by soluble reactive P (SRP) also increased as the percent of dairy waste application fields above a sampling site increased.

Approximately 1,100 communities in the United States have combined sewer and stormwater systems whose capacity may be exceeded during moderate or heavy rainfall. Outflows may occur that can deposit water with varying concentrations of the components of sewage onto public areas, potentially resulting in a range of adverse health effects (Colford et al., 1999). Seasonal and event variations in stream channel area and the contributions of channel precipitation to stream flow were studied on a 106-ha forested headwater catchment in central Pennsylvania. Variations in stream velocity, flowing stream surface width and widths of near-stream saturated areas were periodically monitored at 61 channel transects over a two-year period (Crayosky et al., 1999). Johnson et al. (1999) presented information that suggest non-stormwater source, such as on-site sewage systems and illicit discharges, were major contributors to the contamination of the Rouge River in Wayne County, Michigan.

Weber (1998) reviewed the improvements of water quality of the Greater Cleveland, Ohio area over the past century to the present. In a study of the Ho Chi Minh City of Viet Nam (Phuong et al., 1998) found that the aquatic urban ecosystem is strongly influenced by long-term discharge of untreated domestic and industrial wastewaters, stormwater runoff, accidental spills and direct solid waste dumping.

A study of 22 streams in the Puget Sound Lowland ecoregion in Wash. demonstrated that the physical, chemical and biological characteristics of streams change with increasing urbanization in a continuous rather than threshold fashion (May, 1998). Urbanization history and flood frequencies of four low-order stream basins that underwent significant

urbanization and two other control basins that did not were monitored in the Puget Lowlands between the 1940/50s and 1980/90s. Flood frequencies increased in the urbanized basins and salmon populations decreased while similar results were not documented in the control basins (Moscrip and Montgomery, 1997).

Booth and Jackson (1997) concluded that established methods of mitigating the downstream impacts of urban development may have limited effectiveness. Using continuous hydrologic modeling, detention ponds designed by conventional event methodologies were evaluated and deficiencies in actual pond performance were demonstrated when compared to their design goals. Novotny and Witte (1997) presented a methodology to calculate risk of wet-weather discharges to aquatic ecology (aquatic life). It can be used for ranking pollutants in wet-weather discharges as well for ranking the discharges themselves. The U.S. Environmental Protection Agency (U.S. EPA) (1997a) examined the published literature which revealed that hydrologic impacts on streams were caused by increased impervious areas in urban developments.

Water Environ. & Technol. (1996a) reported that the latest National Water Quality Inventory released by the EPA only showed a slight improvement in the attainment of beneficial uses in the nation's waters. Urban storm runoff was cited as the leading source of problems in estuaries, with nutrients and bacteria being the major problems. Problems in rivers and lakes were mostly caused by agricultural runoff, with urban storm runoff the third ranked source for lakes, and the fourth ranked source for rivers. Bacteria, siltation, and nutrients were the leading problems in the nation's rivers and lakes. Borchardt and Sperling (1996) stressed that many conditions may affect receiving waters from stormwater, specifically physical factors (such as shear stress) and chemical factors (such as oxygen depletion and/or nonionized ammonia).

Temperature and Dissolved Oxygen

Picksley and Deletic (1999) studied the thermal behavior of storm runoff from paved surfaces at two different urban catchments. The thermal trends were explained by equilibrium of thermal influences, based on the physical interaction of runoff and paved surfaces.

The impact to receiving water dissolved oxygen (DO) concentration of intermittent CSO and overflows from a treatment plant were investigated. Data from the River Maun, U.K. showed that an immediate, transient oxygen demand exists downstream of an outfall followed by a separate, delayed oxygen demand (Jubb et al., 1998). The NYC Department of Environmental Protection (DEP) analyzed the feasibility of supplemental aeration in conjunction with a proposed CSO pollution control facility at the Paerdegat Basin, Brooklyn, N.Y. (Gaffoglio et al., 1998a). Aeration as a supplement to conventional CSO controls would address DO concerns, however, the continued discharge of solids during WWF would result in an increased sediment oxygen demand of the basin.

The Harrestrup river in Copenhagen, Den was subject to intensive online investigation of oxygen during both dry and wet weather (Harremoes *et al.*, 1997). An evaluation of oxygen fluctuations demonstrated noncompliance of oxygen standards both during dry and wet weather.

Erosion, Channel Stability, and Sediment

Morrissey et al. (2000) described the sampling program used to confirm a predictive model of metal contaminant build-up (Cu, Pb, and Zn) in the sediments of sheltered urban estuaries in Auckland, New Zealand that have been subjected to urban runoff inflows. The results of their testing showed good general agreement between the model predictions and the observed concentrations of metals in the sediments. The paper by Butcher et al. (2000) described the problems encountered when developing mercury TMDLs for the Arivaca and Pena Blanca Lakes in Arizona. These two lakes lacked point-source discharges of mercury; however, the concentrations of mercury in fish bodies were sufficiently high to trigger TMDL development. The resultant TMDL addressed the problems inherent with controlling pollutants entering the lake when the lake sediment was found to be a primary source of the pollutant. Rate et al. (2000) investigated the concentration of heavy metals in sediments of the Swan River estuary in Perth, Australia. They found that the concentration of lead was elevated near stormwater drain outfalls when compared to areas away from the outfalls, likely due to vehicular material; no similar effect was seen for copper or cadmium. They also noted that since the vast majority of all heavy metals were bound to iron oxides or organic sediments, most of the metals are not bioavailable. The results of the study performed by Rochfort et al. (2000) on the effects of stormwater and CSO discharges on the benthic community showed that the levels of metals and PAHs in sediments below these discharges were high. However, biological effects were not seen - neither the toxicity endpoints nor the benthic community descriptors could be related to the sediment contaminant levels.

Ghani et al. (1999) found that the thickness of a sediment deposit on the bottom of a rigid rectangular channel greatly affects its erodibility of the deposits. They developed channel erosion equations that included terms for the deposit's thickness. Keshavarzy and Ball (1999) studied the entrainment of sediment particles in water and found that the number of entrained particles per unit time per unit area was found to be related to the instantaneous shear stress at the bed. These results were used to modify the Shields diagram. Ashley et al. (1999) investigated the integration of sewer solids' biodegradability into the existing UK waterway protection standards for solids erosion in sewers. This integrated standard would then be used to define the DO criteria in streams and to determine the allowable solids discharge. Rhoads and Cahill (1999) studied the elevated concentrations of chromium, copper, lead, nickel and zinc that were found in sediments near storm sewer outfalls. They noted that copper and zinc concentrations were greater in the bedload compared to the bed material and therefore were more likely to be mobilized during runoff events.

Anecdotal information regarding the impacts of changes in flow on receiving streams were collected, however, not all of it provided conclusive evidence as to the relationship between urbanization and flow-related stream impairment (Frederick and Corrigan, 1998).

Stormwater impacts to streams are not limited to the relatively short duration of runoff events. As an example, sediments can dominate the aquatic physiochemical and biological processing of nutrients; sediment contaminated by stormwater pollutants has a detrimental effect on the receiving-water-biological community. The EPA and other regulatory agencies are attempting to develop sediment quality criteria to determine where excessive concentrations of chemical constituents are present in sediments at sufficient concentrations and in chemical forms to be significantly adverse to the designated beneficial uses of the associated water body. Lee and Jones-Lee (1996a) presented the issues that need to be considered in evaluating the results of a sediment quality assessment procedure to determine whether the toxicity or excessive concentration found is a potentially significant cause of real water quality deterioration in the water body of concern. Maurer *et al.* (1996) analyzed sediment samples collected from five stations in the Newport Submarine Canyon, CA and six nominal 60-m shelf stations to test the following two hypotheses: (1) there is no increase in sediment contaminant concentration with water depth in the Canyon; and (2) there is no difference in contaminant concentration between the canyon and adjacent shelf. The data collected supported hypothesis one and rejected hypothesis two.

Biological Impacts

One impact of stream habitat degradation that could not be accounted for through chemical and biological monitoring would be the effect of elevated flows on habitat availability. A study by Finkenbine et al. (2000) indicated that restoration of stream health in an urban area was best accomplished by the establishment of a healthy buffer zone and the introduction of large woody debris (LWD) into the stream. They found that, after a stream has reached its equilibrium with the flow, detention pond retrofits had few hydrological benefits.

Bailey et al. (1999) investigated the potential toxicity of stormwater runoff from sawmills in British Columbia to juvenile rainbow trout, and found that the toxicity was related to the divalent cation concentration, especially for zinc. They also determined that the zinc toxicity was directly related to the low hardness in the stream, with the range of LC50 of 72 – 272 µg/L associated with hardnesses of 9 – 100 mg/L. Ambrose and Meffert (1999) investigated the fish assemblages in Malibu Lagoon, a small estuary in California, and found that the species diversity and richness were small compared to large estuaries, but were comparable to other small estuaries with less anthropogenic impacts. Hatch and Burton (1999), using field and laboratory bioassays, demonstrated the impact of the urban stormwater runoff on *Hyaella azteca*, *Daphnia magna*, and *Pimephales promelas* survival after 48 hours of exposure. The significant toxicity seen at the outfall site was attributed to the contaminant accumulation in the sediments and the mobilization of the top layers of sediment during storm events. A comparison of highway runoff toxicity with typical urban runoff toxicity was performed by Marsalek et al. (1999). Their study found that approximately 20% of the samples collected at the edge of a multi-lane divided highway (>100,000 vehicles/day) were severely toxic, while only 1% of the typical urban runoff was severely toxic. Skinner et al. (1999) showed that stormwater runoff produced significant toxicity in the early life stages of medaka (*Oryzias latipes*) and inland silverside (*Menidia beryllina*). Developmental problems and toxicity were strongly correlated with the total metal content of the runoff and corresponded with exceedances of water quality criteria of Cd, Cu, W, and Zn.

Ecotoxicological experiments were used by Delbec and Mouchel (1999) to develop a wet-weather quality potential (Φ) that can be used to evaluate oxygen depletions during WWF. The quality potential was used to demonstrate the impact of seasonal hydrological conditions on the occurrence of damaging situations in the River Seine. Pess and Bilby (1999) identified Coho salmon (*Oncorhynchus kisutch*) distribution and abundance in Puget Sound rivers and explained the

distribution by using both stream-reach and watershed-scale habitat characteristics, including the influence of urban areas on the habitat. Tree swallows were used by Secord et al. (1999) to determine the impact of contamination of a watershed and waterway with PCB. The elevated PCB concentrations in the swallows and in the sediments indicate that PCBs in the sediments can be passed up the aquatic food web of the Hudson River ecosystem to the terrestrial and avian wildlife that depend on the River for food. Mallin et al. (1999) documented the effects of Hurricanes Bertha and Fran on the biological community in the Cape Fear area of North Carolina. The natural hurricane effect of swamp water flooding into river basins was reduced DO levels that resulted in fish kills. However, this damage, such as the length of the low DO levels, was considerably increased by anthropogenic practices, including sewage diversions into the rivers and flooding and discharge from swine waste lagoons sited adjacent to the river. The relationship between benthic chlorophyta (*Ulothrix zonata*) and urban stream water quality was demonstrated by Shigemitsu and Hiratsuka (1999).

While exact cause-and-effect relationships have not yet been determined between toxic blooms and algae, dinoflagellates, and similar organisms, evidence suggested that nutrients from agricultural runoff or sewage may stimulate the growth of harmful organisms such as *pfiesteria* spp (Pelley 1998). High P loading to Como Lake, a shallow lake in Minn., from the surrounding urbanized watershed caused eutrophic conditions. Despite efforts to manipulate fish and macrophyte populations, and DO levels in the lake, maintenance of healthy populations of fish, macrophytes, and plankton in the lake will require control of the large P inputs (Noonan, 1998). Heinzmann (1998) described efforts in Berlin, Ger. to reduce P loading to surface water bodies. The response of algae to suspended clay and P loading in an urban lake in N.C. showed that clay tended to reduce algae production, while P tended to increase algae production in this study. However, high P loadings produced nuisance algal blooms and mitigated the adverse effects of high clay loading on algal production (Burkholder et al., 1998).

DNA strand breakage, growth rate, condition index and percentage tissue water were measured in freshwater Asiatic clams (*Corbicula fluminea*) exposed in-situ to a stream that received urban and industrial stormwater runoff versus a non-impacted reference stream. After four weeks, DNA strand lengths of the exposed clams were significantly shorter than from reference clams which suggested a reduction in DNA integrity in the exposed clams, possibly indicating exposure to genotoxic chemicals, while no significant differences were observed in the growth rates (Black and Belin, 1998). Loumbourdis and Wray (1998) detected high concentrations of Cu, chromium, molybdenum, Zn, manganese, and aluminum, in the tissues of frogs living in a small river in Macedonia, north. Greece, corresponding to highly polluted areas. The main sources of the river pollution seem to be fertilizers containing heavy metals as trace elements, pesticides with heavy metals in their formula, urban runoff, and various light industries along the river. The bioaccumulation and toxicity of Zn in *Spirogyra Fluvialis* Hilse (chlorophyta), from two populations in the River Seyhan, Adana, Turkey, showed little difference in Zn bioaccumulation between *Spirogyra* from a site showing mild organic pollution or that from a site subjected to considerable inputs from urban and motorway runoff. Cellular damage was evident in *Spirogyra* subjected to 0.5 mg/L Zn, and increased with increasing Zn concentration (Saygideger 1998).

Wernick et al. (1998) compared land-use indicators to streamwater nitrate-N levels in the Salmon River watershed near Vancouver, British Columbia, Can. and found that urbanized areas, as indicated by septic tank density, contribute to elevated nitrate-N levels in an urban-rural fringe environment. In the main tributary of the Salmon River, nitrate-N levels correlated with urban land use, but not with agricultural land use as indicated by animal unit density, indicating that urban land use is the primary source of nitrate-N in that basin.

Winter and Duthie (1998) documented the adverse effects of urbanization on periphyton and macroinvertebrate community structure in Laurel Creek, a rapidly urbanizing subwatershed of the Grand River in southern Ont., Can. Pesacreta (1997) monitored the benthic life of the urban Morgan Creek of Carrboro and Chapel Hill, N.C. The macroinvertebrate *Pteronarcys dorsata*, which is intolerant to pollution was observed as a sub-lethal toxicity indicator. Schultz (1998) presented a brief overview of how urban streams got into their current predominantly degraded conditions and the activities and results of several recent programs aimed at rehabilitation of urban streams.

A correlation between runoff events and poor water quality in Lake Michigan established that runoff events have had significant impact on the drinking-water quality in Milwaukee, Wis. where 400,000 people were infected with *cryptosporidiosis* in 1993 (Christensen et al., 1997). *Giardia* and *Cryptosporidium* were monitored monthly for two years to determine their occurrence in the Allegheny and Youghiogheny Rivers of Pennsylvania, their source, and the efficiency of their removal by the Pittsburgh Drinking Water Treatment Plant. Sources investigated included a dairy farm stream, wastewater treatment plant (WWTP) effluent, and several samples from CSO (States et al., 1997).

Macrobenthic communities were surveyed in 1987-88 as part of a comprehensive study of fish kills and water quality in the upper Trinity River of Texas (Davis, 1997). While some impact was evident in certain reaches from pesticides, dissolved metals, and WWTP effluents, the overall impacts were relatively slight on a long-term basis and a high aquatic-life use was attained at most sites. The Bloomington and Normal Water Reclamation District of McLean County, Ill. began an ongoing biological survey of Sugar Creek in 1983 (Callahan 1997). Improvement in the fish community was linked to the discontinuation of effluent chlorination through an annual exemption in 1991, while the addition of nitrification, construction of CSO controls, and tertiary filter failure did not demonstrate immediate and directly attributable affects. In many southern California salt marshes, increased freshwater inflows have promoted the establishment of exotic plant species. Kuhn and Zedler (1997) proposed that salt applications may be a practical method for controlling exotic plant invasions in areas receiving urban stormwater runoff or other unwanted freshwater inflows.

Hellou *et al.* (1997) exposed rainbow trout to waste crankcase oil, a recognized source of PAH contamination in urban stormwater runoff. The accumulation of compounds in muscle tissue, the elimination of bile metabolites, the activity of 7-ethoxyresorufin O-deethylase (EROD) in liver, and morphometric variables were compared at different concentrations and times of sampling. Jennings *et al.* (1997) extracted ten pollutant phenols from an oil-refinery discharge, urban stormwater, and WWTP effluent with the highest concentration found in the WWTP effluent. Bioaccumulation experiments were conducted using the mussel, *Mytilus edulis* and the fish, *Trachurus novaezelandiae* with similar concentrations, and both species depurated all accumulated phenols to concentrations below detection within 24 h when placed in clean seawater. Magaud *et al.* (1997) developed a quantitative model of the instantaneous death probability of juvenile rainbow trout as a function of time, concentrations of unionized ammonia (NH_3), and dissolved oxygen (DO). This model found the survival probability of rainbow trout exposed simultaneously to NH_3 and low DO was lower than the predicted survival probability derived from the simple addition of the individual effects. Moore and Farris (1997) conducted 48-h acute-toxicity tests with *Ceriodaphnia dubia* (cladoceran) and *Pimphales promelas* (fathead minnow) on stormwater runoff, laboratory synthetic water, and irrigation (ground) water with the herbicide Stam®M-4 (active ingredient Propanil [3',4'-dichloropropionanilide]). No effects on survival were observed in this study following 48-h toxicity testing with the stormwater. Siewicki (1997) estimated the risks posed by fluoranthene (a four-ring PAH) in urban stormwater runoff by modeling and exposure assessment of a portion of Murrells Inlet in South Carolina. Results suggested bioconcentration of fluoranthene in oysters is related to adjacent land uses and can be predicted by understanding the major factors affecting its transport and fate. An approach is described to test alternate landscape modifications for minimizing impacts on both resident fauna and seafood consumers. Villeneuve *et al.* (1997) used an in vitro bioassay with PLHC-1 (*Poeciliopsis lucida*) fish hepatoma cells to assess potential toxic potency of aryl hydrocarbon receptor (AhR-active) compounds, collected by semipermeable membrane devices (SPMD) exposed to Lincoln Creek water Milwaukee County, Wis. as part of a comprehensive study on the effects of stormwater runoff. A log-log correlation of total PAH and toxic potency of dialysates (expressed as bioassay-derived 2,3,7,8-tetrachlorodibenzo-p-dioxin equivalents [TCDD-EQ]) yielded an $r^2 = 0.802$ and empirical evidence suggested that AhR-active PAH can account for about 20% — 50% of the potency observed.

The detection and assessment of pollution in the aquatic environment and their effects upon the biological community are rapidly becoming a central focus of state agency water-resource programs. Bioassessments are particularly useful because they reflect the condition of the resident biota from cumulative effects as a result of both nonpoint and point source impacts (Barbour, 1996). Barbour and Stribling (1996) presented a summary of the physical instream and riparian habitat features of a visual-based habitat assessment and their relationship to and influence on biological communities. The quality and stability of stream and riparian-physical habitat, rated in relation to unimpaired streams of similar site-specific and regional characteristics, provide an estimate of the biological potential of a stream system. Preliminary results of research on the application of an aquatic-invertebrate-bioassessment protocol suitable for wetland conditions indicate that ecological integrity of wetlands is affected by the amount of impervious surface in the watershed and that aquatic-macroinvertebrate communities serve as indicators of wetland condition (Hicks and Larson, 1996). Jones *et al.* (1996) reported that macroinvertebrate bioassessment indicated substantial impairment of streams in a heavily-suburbanized Virginia watershed relative to a companion forested watershed, while a lightly developed adjacent watershed showed an intermediate level of impairment. Severe impairment of the benthic- macroinvertebrate community was found further downstream below the discharge of large quantities of unmitigated stormwater. McCarron *et al.* (1996) discussed the need and rationale for alternative sampling and assessment procedures that provide a more ecologically-based manner of determining the cumulative environmental effects of nonpoint sources of pollution. The Florida Department of Environmental Protection's multi-year effort to refine and enhance current biological-community-assessment methods was described.

Evaluation of Central Texas streams using the bioassessment techniques developed for perennial streams indicates that these methods fail to accurately assess the degree of impact on the local community structure due to biological seasonality and intermittent flow (Hansen, 1996). Current assessment techniques need to be modified or new techniques developed for intermittent streams that will enable investigators to distinguish between aquatic-biota impacts due to natural, environmental variations and impairments related to anthropogenic activities in the local watershed. A study was conducted to provide the Texas Natural Resource Conservation Commission with information concerning the nonpoint source discharges from the City of Uvalde to assist in developing appropriate rules to implement provisions in the Texas Water Code requiring cities with populations over 5,000 to develop and submit Water Pollution Control and Abatement Plans (Coonan *et al.*, 1996). The results indicated that the samples taken from areas subject to urban storm runoff from the City exhibited statistically lower concentrations for numerous parameters; an impact on aquatic communities in the urban storm-runoff receiving-water was not observed.

Claytor (1996a) summarized the approach developed by the Center for Watershed Protection as part of their EPA sponsored research on stormwater indicators (Claytor and Brown, 1996). The 26 stormwater indicators used for assessing receiving-water conditions were divided into six broad categories: water quality, physical/hydrological, biological, social, programmatic, and site, and were presented as tools to measure stress (impacting receiving waters), to assess the resource itself, and to indicate stormwater control program implementation effectiveness.

Pereira *et al.* (1996) assessed the effects of human activities and land use on the water quality of the San Joaquin River and its major tributaries. This study focused on pesticides and organic contaminants and examined water, particulate forms, sediment, and bivalve shellfish.

The biological communities in Delaware's Piedmont streams have been severely impacted by stormwater, after the extent of imperviousness in the watersheds exceeds 8-15%, according to a review article (Claytor 1996c). If just conventional water quality measures are used, almost all (87%) of the state's nontidal streams supported their designated biological uses. However, when biological assessments are included, only 13% of the streams satisfactorily meet their uses.

Weed invasion in the bushland surrounding the Lane Cove catchment in Australia was related to contamination of the floodplain by heavy metals and nutrients, plus increased flooding from the urban development surrounding the bushland (Riley and Banks, 1996). Aesthetics has historically been difficult to quantify in urban receiving-water studies, but it has been an important parameter for many uses, especially recreation. Heidtke and Tauriainen (1996) developed an aesthetic rating system for the Rouge River (Detroit, MI), using a combination of water clarity, water color, odor, and visible debris. Preliminary work suggests that the index is an effective tool for tracking time and space trends in aesthetic characteristics of the receiving water and for public education.

Microbiological impacts

An investigation of shoreline microbiological contamination conducted by Robertson *et al.* (2000) in Orange County, California, showed that the likely cause of the elevated fecal coliforms was dry weather urban runoff from the San Gabriel River and storm drains up the coast, rather than the Orange County's WWTP effluent ocean outfall. As a result of seventeen *E. coli* O157:H7 cases, investigation of the potential contamination on the Mar del Plata beaches due to combined sewer overflows was performed by Perez Guzzi *et al.* (2000). Their investigation detected no *E. coli* O157:H7, although other strains of *E. coli* were detected in 75% of the samples. None of the 98 strains detected in the outfalls were the strains that were known to cause human illness. However, the presence of *E. coli* in the drainage water indicated fecal contamination and the resulting potential for illness should a toxic strain be present in the sewage. Rose *et al.* (2000), through climate and epidemiological records, demonstrated a potential correlation between extreme precipitation events and waterborne disease outbreaks. The authors found that statistically significant relationships could be developed between large precipitation events and waterborne disease outbreaks for both surface and ground water, although the relationship was much stronger for surface water outbreaks. The impact of urban runoff and the potential resuspension of settled parasites in Paris rivers at the drinking water intakes was investigated by Rouquet *et al.* (2000). Their results showed that parasite sedimentation was high, but that resuspension due to urban runoff was also likely. Rangarajan *et al.* (2000) developed a model for the City of Edmonton for predicting the impact of rainfall on combined sewer overflows and hence on river water quality. This model would be used to predict elevated fecal coliforms in the river, and hence, for determining when microbiological standards for recreational waters would be exceeded.

Crabill *et al.* (1999) presented their analysis of the water and sediment in Oak Creek in Arizona, which showed that the sediment fecal coliform counts were on average 2200 times greater than that in the water column. Water quality standards

for fecal coliforms were regularly violated during the summer due to the high recreational activity and animal activity in the watershed, as well as the storm surges due to the summer storm season. Lemke and Leff (1999) analyzed the bacterial populations at five sites, including two in disturbed urban streams. The results indicated that anthropogenic disturbance of watershed and stream can alter some bacterial populations (*Acinetobacter calcoaceticus*) but not others (*Burkholderia cepacia*, *Pseudomonas putida*). Haile et al. (1999) presented the results of an epidemiological cohort study of swimmers in Santa Monica Bay, California where untreated urban runoff from Los Angeles was discharged. Higher risks of upper respiratory and gastrointestinal infections were found for swimmers near storm-drain outfalls, in waters with a low ratio of total to fecal coliforms, and in waters where enteric viruses were detected. Herrmann et al. (1999b) demonstrated through modeling that, for a German city with a combined sewer system, blackwater separation by vacuum toilets and urine separation can reduce nutrient discharges during overflow events by 90%, especially in the summer when the river water may contain up to 50% sewage. These reductions in nutrient discharges might improve the river water quality sufficiently to meet swimming water quality criteria during most, if not all, of the year.

Water Environ. & Technol. (1996c) reported on an epidemiology study conducted at Santa Monica Bay, CA that found that swimmers who swam near stormwater outfalls were 50% more likely to develop a variety of symptoms than those who swam 400m from the same outfalls. This was a follow-up study after previous investigations found that human-fecal waste was present in the stormwater-collection systems. *Environ. Sci. & Technol.* (1996b) also reported on this Santa Monica Bay study. More than 1% of the swimmers who swam in front of the outfalls were affected by fevers, chills, ear discharges, vomiting, and coughing, based on surveys of more than 15,000 swimmers. The health effects were more common for swimmers who were exposed on days when viruses were found in the outfall-water samples.

Eggleston et al. (1996) reported that closures of the Boston area's Tenean Beach were due to either exceedance of Massachusetts' fecal-coliform limit (200MPN/100mL) or both the fecal coliform and the EPA's criterion for *Enterococcus* in bathing beaches in marine waters (104 MPN/100mL). It was cited that past epidemiological research demonstrating fecal-coliform concentration to be a poor indicator of public-health risk in marine waters and the exceedance of the EPA's *Enterococcus* standard as the basis for questioning the degree of public-health risk posed by swimming in these waters. Su et al. (1996) further document problems with the fecal-coliform test. It was concluded that the *E. coli* criteria can do a superior job of reflecting the public perception of a desirable water body for swimming.

Chemical Impacts

Work by Standley et al. (2000) demonstrated that the source of the impacts on a receiving water could be determined using molecular tracers. Polycyclic aromatic hydrocarbons were seen to be excellent tracers for evaluating pollution from urban runoff, while caffeine plus consumer product fragrance materials were excellent markers for WWTP effluent. The investigation by Foster et al. (2000) showed that higher amounts of PCBs, PAHs and organochlorine pesticides in the Anacostia River were associated primarily with the particulates and occurred during high flow events. Analysis of the PAHs showed that they were characteristic of weathered or combusted petroleum products. Aromatic hydrocarbons in urban runoff were found to be likely sources of PAH fluxes to the tidal waters of Chesapeake Bay. O'Meara et al. (2000) described the work done to remove 556,000 Mg of sediment and 12,700 kg of fish contaminated with PCBs from Newburgh Lake in Wayne County, Michigan. The result was that the lake was found to be fit for human recreational activity. Shinya et al. (2000) investigated the concentrations of metals and PAHs in the runoff from four urban-highway rainfall drains. The results showed a first flush of both metals and PAHs. Most of the metals were tied up with the particulate matter, as were the higher molecular weight PAHs. Mutagenicity was appreciably associated with the PAHs in the particulate fraction, although the dissolved fraction also showed positive mutagenic response.

The impacts of combined sewer overflow solids were predicted using a model that could describe the solids movement and the erosion of previously-deposited solids in the sewers (Saul et al. 2000). This model was then used to predict the quantity and arrival time of the first flush of sewer solids into a receiving water after a rainfall.

Oberts et al. (2000) reviewed the impacts of snowmelt on urban water quality. They reviewed research on urban snowpacks accumulating large quantities of solids and other pollutants from sources such as airborne fallout, vehicular deposition, and applied grit and salt. They also reported on instances where the first flush of snowmelt has been found to be highly toxic and where water quality deterioration due to snowmelt runoff have been documented.

Stieber et al. (1999) statistically related the pollutant load in urban runoff to interevent dry period and rainfall intensity with the ultimate goal of developing a simple relationship between the rain variables and the pollutant loads. The relationship could be used by planners and engineers to evaluate the effectiveness of pollutant reduction mechanisms.

Bamford et al. (1999) investigated the fluxes of PAH at the air-water interface of the Patapsco River and found that the fluxes were highest adjacent to stormwater discharges due to the elevated concentrations of PAH in the stormwater runoff. A major source of the PAH, benzo(ghi)perylene, pyrene and fluoranthene in the rivers in the Paris metropolitan area was found by Ollivon et al. (1999) to be car-park dust due to motor vehicle combustion. During heavy rainfall events, PAH primarily were leached from urban surfaces and transported to the rivers. Zheng et al. (1999) related the high concentrations of petroleum hydrocarbons and PAH in Hong Kong marine sediments to the heavily urbanized or industrialized areas surrounding the most heavily polluted sites. They showed that the oil and its products were the major sources of hydrocarbons in sediments. Stormwater runoff from an urban highway in Xi'an, China was shown by Zhao et al. (1999) to contain BOD, COD and suspended solids concentrations at least as strong as typical domestic effluents. However, the biodegradability of the organic compounds in the runoff (BOD:COD = 0.167) was low. Regression equations were developed for BOD and COD and for suspended solids and COD in urban runoff from the highway. Gupta et al. (1999) investigated the sources of pollutants to Talkatora Lake in Jaipur, India. They found, using a mass balance of the lake, that the major cause of pollution to the lake was the first flush of stormwater runoff from the adjacent residential and commercial areas.

Bendoricchio et al. (1999) demonstrated that nutrient concentrations in runoff varied during rain events and that the deterioration of water quality in the Lagoon of Venice, Italy, was related to the diffuse pollution sources in the watershed. As the point sources of pollution were controlled, the relative importance of NPS increased, and effectiveness of the Lagoon restoration would depend on controlling the diffuse sources of the nutrients. A water quality index (WQI) was developed by Peters and Kendell (1999) for streams in the Atlanta, Georgia region, and the sampling data showed that the WQI for nutrients was best for the low-density residential areas and worst for the industrial area. Yung et al. (1999) investigated the physico-chemical and biological changes in Victoria Harbor, Hong Kong and found that water temperature, total and ortho-phosphorus, and fecal bacteria were increasing, while pH, total nitrogen, TKN, BOD and chlorophyll a were decreasing. However, sampling sites not in the main Harbor did not reflect these trends, although all sites reflected the fact that Victoria Harbor and its vicinity were polluted by sewage effluent, stormwater runoff, marine traffic, construction, and industrial activities.

Crosbie and Chow-Fraser (1999) investigated the impact of land use on the water and sediment quality in 22 marshes in Ontario, Canada. The concentration of inorganic solids, sediment phosphorus, metolachlor, and ionic strength were positively correlated with the percentage of agricultural land in the watershed, while the concentrations of PAH were positively correlated with the percentage of urban land. Heal (1999) demonstrated the accumulation of copper, nickel and lead in the sediments of a wetland and two detention ponds receiving urban storm runoff in Scotland. Sediment metals concentrations, however, were highly variable within each structure, possibly indicating short-circuiting through the ponds and wetland. Platinum, palladium and rhodium were found in road sediments by Rauch et al. (1999) with their concentrations increasing since 1984. The increase in bioaccumulation of rhodium in *Aseltus aquaticus* in urban rivers was linked to the increased sediment concentrations of these automobile-derived metals. Shafer et al. (1999) investigated the partitioning of trace metal levels (Al, Cd, Cu, Pb, and Zn) in Wisconsin rivers and found that the concentrations in the rivers were comparable to recent data collected in the Great Lakes and other river systems where 'modern' clean methods were used for sampling and analysis. They also found that the variation in the partitioning coefficients of each metal between sampling locations could be explained by the amount of anthropogenic disturbance in the watershed and by the concentration of dissolved organic carbon (DOC) in the water.

Arid western rivers have many characteristics that distinguish them from rivers in more temperate areas. The Denver area's South Platte River, in which flow is dominated by municipal effluent, has the following characteristics: nutrient abundance; wide, shallow and unshaded channel; high primary productivity produces variations on pH that can have a strong influence on nonionized-ammonia concentrations (Harris et al., 1996).

Inaba et al. (1997) studied the effects of trace metals, e.g., cobalt (Co) and Fe in sanitary wastewater. Elevated concentrations have been shown to increase the frequency of algal blooms in water bodies. Haygarth and Jarvis (1997) studied the transfer of P and N by stormwater runoff from cattle grasslands and concluded that grassland soils are a significant source of diffuse P inputs to surface and estuarine waters and may cause eutrophication.

The physical and chemical properties of sediment in a stormwater pond were studied. Analysis of the sediment determined that Cr, Cd, Cu, Fe, Pb, manganese (Mn), Ni, and Zn were present (Marsalek et al., 1997). In a study to investigate the fate of infiltrating stormwater runoff, natural-organic matter facilitated metal transport into near surface soils (Igloria et al., 1997). The metal transport was a function of volume and depth of stormwater and increased

concentrations of natural-organic matter allowed for greater metal attenuation.

Hay and Battaglin (1996) described how an integrated system consisting of a large historical receiving-water-quality database, a geographic-information system (GIS), a scientific-visualization system, and multimedia software are used to produce an interactive data-analysis tool. The integrated system allows users to analyze the data in the U.S. Geologic Survey's (USGS) National Stream Quality Accounting Network (NASQAN), describes the water quality of the Nation's streams and rivers on a systematic basis and to identify temporal trends in the concentration of measured constituents. Stream water-quality data from NASQAN and USGS's Hydrologic Benchmark network are now available on CD-ROM (Alexander *et al.*, 1996). These networks provided some of the best available data for quantifying changes in the water quality of major United States streams during the past 20-30 years, estimating the rates of chemical flux from major continental watersheds of the United States, and investigating relations between water quality and streamflow as well as water quality to watershed characteristics and pollution sources.

Sampling and monitoring of New York City's Jamaica Bay have confirmed the eutrophic state of some areas of the Bay (Fitzgerald *et al.*, 1996). It is known that the probable root causes of this problem are both the extremely high nutrient loading to the Bay from anthropogenic sources as well as the lack of adequate flushing also resulting from human intervention.

Glazewski and Morrison (1996) presented results showing the effects of photoreduction of Cu in urban streams. It was concluded that pollutant speciation and potential toxicity of Cu, Cr, and Fe is greatly affected by photoreduction reactions.

Toxicity

Milam *et al.* (2000) investigated the effects of several pesticides (chlorpyrifos, malathion, Permethrin(R), Abate(R), Scourge(R), B.t.i. and Biomist(R)) on both standard toxicity-testing organisms (*Ceriodaphnia dubia*, *Daphnia magna*, *Daphnia pulex*, and *Pimephales promelas*) and resident mosquito fish and mosquito larvae. They demonstrated that the current pesticide application rates were sufficient to affect non-target organisms when the pesticides were washed off in stormwater runoff.

Toxicity of river sediment near major cities on the Mississippi River was evaluated, both up- and down-river of the cities, and was not found to be toxic to the organisms studied (Winger and Lasier, 1998). Most stormwater samples from Ballona Creek which is one of the largest sources of stormwater inputs to Santa Monica Bay, Calif. were toxic (Jirik *et al.*, 1998). Receiving water samples were also toxic, with the magnitude of effects generally corresponding to the concentration of runoff present. The study implicated divalent trace metals, particularly Zn as the probable toxic constituents.

One of the key objectives of the Chesapeake Bay restoration effort is to reduce the impacts of toxicants. Alden and Hall (1996) described the Toxics Reduction Strategy based on water-column- and sediment-chemical analyses, benthic-community health, and fish-body burdens. More than 40% of the sites have displayed some degree of water-column toxicity and about 70% of the sites have displayed sediment toxicity. Garries *et al.* (1996) further described how the list of Toxics of Concern was developed for Chesapeake Bay.

The need for endpoints for assessments using multiple stressors was discussed by Marcy and Gerritsen (1996). Five watershed-level ecological-risk assessments were used to develop appropriate endpoints based on specific-project objectives. Dyer and White (1996) also examined the problem of multiple stressors affecting toxicity assessments. It was thought that field surveys rarely can be used to verify simple single-parameter-laboratory experiments. A watershed approach integrating numerous databases in conjunction with *in-situ* biological observations to help examine the effects of many possible causative factors was developed. *Environ. Sci. & Technol.* (1996a) reported that toxic-effect endpoints are additive for compounds having the same "mode of toxic action", enabling predictions of complex-chemical mixtures in water. According to EPA researchers at the Environmental Research Laboratory in Duluth, MN, there are about five or six major action groups that contain almost all of the compounds of interest in the aquatic environment. Much work still needs to be done but these new developing tools may enable the instream toxic effects of stormwater to be better predicted.

Ireland *et al.* (1996) found that exposure to UV radiation (natural sunlight) increased the toxicity of PAH-contaminated-urban sediments to *C. dubia*. The toxicity was removed when the UV wavelengths did not penetrate the water column.

Toxicity was also reduced significantly in the presence of UV when the organic fraction of the stormwater was removed. Photo-induced toxicity occurred frequently during low-flow conditions and wet-weather runoff and was reduced during turbid conditions.

Johnson *et al.* (1996) and Herricks *et al.* (1996a) described a structured-tier-testing protocol to assess both short-term and long-term wet-weather-discharge toxicity that was developed and tested. The protocol recognizes that the test systems must be appropriate to the time-scale of exposure during the discharge. Therefore, three time-scale protocols were developed, for intraevent, event, and long-term exposures. The use of standard-whole-effluent-toxicity (WET) tests were found to over-estimate the potential toxicity of stormwater discharges.

Schueler (1996c) summarized *in-situ* assessment methods of stormwater-impacted sediments. The use of *in-situ*-test chambers, using *C. dubia* eliminates many of the sample disruption problems associated with conducting sediment-toxicity tests in the laboratory. Arhelger *et al.* (1996) presented the results of a study of toxicity in the Houston Ship Channel area that included analyses of water and sediment toxicity. A comparison of the toxicity of sediments from all stations to *Ampelisca abdita* versus all available physical and chemical data led to the conclusion that the toxicity was most likely related to sediment-oxygen demand.

The results of studies conducted by Crunkilton *et al.* (1996) were inconclusive in determining if toxicants alone played a role in observed degradation of a stream community. This question was posed because most stormwater-remediation efforts implemented to protect streams have focused on mitigating physical degradation of habitat. In an assessment of the response of aquatic organisms to short-term exposures to urban storm runoff, Herricks *et al.* (1996b) found that toxicity testing in single events may not be predictive of long-term effects in receiving waters but multiple event analysis provides information on sources and variability of toxicity that is useful in watershed management. Similarly, Herricks *et al.* (1996c) found that commonly used toxicity-testing techniques of long-exposure times to constant concentrations will not adequately predict short-term toxicity.

The effects of stormwater on Lincoln Creek, near Milwaukee, WI, were summarized by Claytor (1996b). The Creek drains a heavily-urbanized watershed of 19 mi² and is 9-mi long. On-site-toxicity testing was conducted with side-stream flow-through aquaria using fathead minnows plus instream-biological assessments along with water- and sediment-chemical measurements. The continuous flow-through-mortality tests indicated no toxicity until after about 14 days of exposure, with more than 80% mortality after about 25 days, indicating that short-term toxicity tests likely underestimate stormwater toxicity. The biological- and physical-habitat assessments supported a definitive relationship between degraded-stream ecology and urban storm runoff.

Rainbow (1996) presented a detailed overview of heavy metals in aquatic invertebrates. It was concluded that the presence of a metal in an organism cannot directly prove whether that metal is poisoning the organism. However, if compared to concentrations in a suite of well-researched biomonitors, it is possible to determine if the accumulated concentrations are atypically high, with a possibility that toxic effects may be present. Allen (1996) also presented an overview of metal-contaminated-aquatic sediments. This book presents many topics that would enable the user to better interpret measured heavy-metal concentrations in urban-stream sediments.

Pitt *et al.*, (1996b) reported on various laboratory-toxicity tests using 20-stormwater and -CSO samples. It was found that the most promising results are associated with using several complementary tests, instead of any one-test method. However, simple screening-toxicity tests are useful during preliminary assessments or for treatability tests.

A number of papers presented at the 7th International Conference on Urban Storm Drainage, held in Hannover, Germany (Sieker and Verworn 1996), described receiving-water studies that investigated organic- and heavy-metal toxicants. Handová *et al.* (1996) examined the bioavailability of metals from CSOs near Prague, Czech Republic. The results were compared with biomonitoring. The metals were ranked according to their mobility as: Cd (95%), Zn (87%), Ni (64%), Cr (59%), Pb (48%), and Cu (45%). The mobile fraction was defined as the metal content that was exchangeable, bound to carbonates, bound to iron and manganese oxides, and bound to organic matter. Boudries *et al.* (1996) and Estèbe *et al.* (1996) investigated heavy metals and organics bound to particulates in the River Seine near Paris, France. The Paris CSOs caused a significant increase in the aliphatic and aromatic hydrocarbons bound to river sediments. The high flows during the winter were associated with lower heavy metal associations with the sediment, compared to the lower summer-flow conditions. These differences were found to be due to dilution of the CSOs in the river and to the changing contributions of rural versus urban SS during the different seasons.

Habitat Management and Restoration

A number of stream restoration efforts have been carried out in small watersheds in Maryland for the past ten years. The goal of virtually all of the restoration projects was to reduce high sediment supply from bank and bed erosion and to increase sediment transport, thus restoring a condition of equilibrium between sediment supply and sediment transport.

Bragg and Kershner (1999) investigated another aspect of biological impacts – the impact on the habitats of aquatic life – and they found that coarse woody debris in riparian zones can be used successfully to maintain the integrity of these ecosystems. Larson (1999) evaluated the effectiveness in urban areas of these habitat restoration activities using large woody debris and found that in urban areas, the success of restoration may be hindered by the high sediment loads and increased flow associated with urbanization. Markowitz et al. (1999) documented the CSO Long Term Control Plan implemented by the City of Akron, Ohio which focused on habitat preservation and aquatic life use of the receiving waters. The plan included these non-traditional alternatives: riparian setbacks in undeveloped areas, stream restoration, linear parks or greenways and artificial riffles for stream aeration, and were found to cost less than five percent of the typical cost of controlling CSO flows. A methodology to investigate the chronic and cumulative degradation of the river Orne due to CSO and urban runoff was presented by Zobrist et al. (1999), with the results being used to evaluate management activities. O'Meara et al. (1999) reported on the restoration of Newburgh Lake on the Middle Rouge River in Wayne County, Michigan. The \$11.8-million restoration consisted of removing PCB-contaminated sediment and fish, construction of new fish habitat, and restocking of beneficial fish and aquatic plants. Xu et al. (1999) reported on the improvement plan being used for a river passing through the downtown area of a city in Western Japan and the problems that were inherent with developing a compromise strategy between flood control and mitigation and the desire to have an attractive waterway through the city. The final improvement plan recommended construction of a new flood drain tunnel and a new underground flood control reservoir.

Cianfrani et al. (1999) used a GIS system to document the results of a comprehensive inventory of the natural resources of the Fairmount Park (Philadelphia, Pennsylvania) stream system, including vegetation communities, fish, aquatic and terrestrial insects, birds, mollusks, amphibians, reptiles, and streams. The stream assessment also included the characterization of stream reaches by in-stream habitat, geomorphology and riparian zone. This GIS inventory then was used in planning the restoration of sites in the Fairmount Park system. Derry et al. (1999) reported on the habitat management strategies implemented by the City of Olympia, Washington, to control the degradation of aquatic habitats by urban stormwater runoff. These management strategies provided a basis for resolving the conflict between growth and the protection of aquatic resources. Ishiakwa et al. (1999) reported on the efforts to restore the hydrological cycle in the Izumi River Basin in Yokohama, Japan while Saeki et al. (1999) have documented the efforts of the Tokyo Metropolitan Government and its Basin Committee to restore the natural water cycle in the Kanda River. Kennen (1999) investigated the relationship between selected basin and water-quality characteristics in New Jersey streams and the impact on the macroinvertebrate community and its habitat. He found that urban areas had the greatest probability of having impacted stream areas, with the amount of urban land and the total flow of treated sewage effluent being the strongest explanatory variables for the impact. He also found that levels of impairment were significantly different between the Atlantic Coastal Rivers drainage area and the Lower Delaware River drainage area.

Jarrett et al. (1999) analyzed the data collected from 1991 through 1998 as part of the stream-monitoring program implemented in Louisville and Jefferson County, Kentucky. They found that recreational contact standards for fecal coliforms were exceeded during WWF and that much of the pollutant loadings of suspended solids and BOD were also contributed by WWFs. However, they found that the nutrient loadings were more varied with some impact seen from wastewater treatment plants. The concentrations of phosphate, total phosphorus, and total volatile solids in the streams were reduced as more of the watershed was sewered. Reduction of eutrophication through the treatment of stormwater runoff with storage facilities and wetlands for Lake Biwa was proposed by Hidaka et al. (1999). It was estimated that this storage and treatment could reduce the COD load to the lake by nearly 70%. However, wetlands could be overloaded and the water quality of its effluent degraded, as demonstrated by Noguchi et al. (1999) in their study of the regulation pond/wetland in Isahaya Bay, Japan. In order to prevent eutrophication of the regulatory pond it was found to be necessary to control nonpoint sources of nutrients in runoff.

Changes in physical stream channel characteristics can have a significant effect on the biological health of the stream. Schueler (1996a) stated that channel geometry stability can be a good indicator of the effectiveness of stormwater control practices. In addition, once a watershed area has more than about 10-15% effective impervious cover, noticeable changes in channel morphology occur, along with quantifiable impacts on water quality, and biological conditions. Stephenson

(1996) studied changes in stream-flow volumes in South Africa during urbanization. Increased stormwater runoff, decreases in the groundwater table, and dramatically decreased times of concentration were found. The peak flowrates increased by about two-fold, about half caused by increased pavement (in an area having only about 5% effective-impervious cover), with the remainder caused by decreased times of concentration.

Environmental Effects of CSO and SSO

CSO and SSO can have damaging impacts on receiving waters. Sanudo-Wilhelmy and Gill (1999) compared current pollutant concentrations in the Hudson River Estuary, New York with concentrations measured in the 1970's. The concentrations of Cu, Cd, Ni, and Zn have declined, while concentrations of dissolved nutrients (PO_4) have remained relatively constant during the same period of time, suggesting that wastewater treatment plant improvements in the New York/New Jersey Metropolitan area have not been as effective at reducing nutrient levels within the estuary. Rather than inputs from point sources, the release of Pb and Hg from watershed soils, and Ni and Cu from estuarine sediments, may represent the primary contemporary sources of these metals to the estuary. Approximately 1,100 communities in the United States have combined sewer and stormwater systems whose capacity may be exceeded during moderate or heavy rainfall. Colford et al. (1999) proposed and applied three analytic methods to evaluate the impact of such outflows on public health. David and Matos (1999) discussed the difficulties of modeling and regulating the effects of CSO and stormwater discharges on the water quality in Portugal's rivers. Emphemeral river flows, rainfall patterns that differ from north to south, the effects of pollutant transport dynamics in sewers and pavements, and bed river resuspension during storms all influence river water quality. To understand the effect of CSO on the river Seine (France), a characterization of effluent in terms of organic matter and bacterial biomass was carried out during several sampling campaigns performed in a combined sewer located in Parisian suburbs under wet- and dry-weather conditions. The only two small differences in relative composition that could be observed between dry and wet weather were slightly lower content of organic carbon in suspended solids and a lower biodegradability of this material during rain events (Servais et al. 1999). Vollertsen et al. (1999a) characterized the biodegradability of combined-sewer organic matter based on settling velocity. Fast settling organic matter, which represents the largest fraction of the organic material, was found to be rather slowly biodegradable compared to the slow settling organic fraction. The biodegradability of sewer sediments was argued to be taken into account for detailed characterization when dealing with CSO impacts. Vollertsen et al. (1999b) investigated the effects of temperature and DO on kinetics of microbial transformation processes of suspended sewer sediment particles. No differences between sewer-sediment particles, wastewater particles and wastewater were found for the oxygen-saturation coefficients examined.

By means of measurements and numerical simulations, it was shown that the first flush of dissolved compounds effect caused a significant impact of dissolved compounds on the receiving water, when a CSO occurs, and also on the wastewater treatment plant when the sewer network was flat and catchment area was big (Krebs et al., 1999). Mason et al. (1999) showed that the Chesapeake Bay was an efficient trap for mercury. However, in the estuary, methylation of the mercury occurred, the Bay became a source of methylmercury, and on a watershed scale, only about 5% of the total atmospheric deposition of mercury was exported to the ocean. Venkatesan et al. (1999) investigated the potential for using sediment cores to determine the history of chlorinated pesticide and PCB application in a watershed. They found that the sediment cores accurately reflected the length of use of these chemicals in the watershed, and that the surface sediment layer, after mixing and resuspension was accounted for, reflected the reduction in use that had occurred during the last few years.

Bellefleur et al. (1999) summarized the data available on the water quality of combined sewer flow in Roeschwoog. The data that these flows impacted the physical and chemical water quality of the Sauer; however, an impact of CSO on the biological integrity was not easily seen. Classification of the rainfall into eleven types of events allowed the investigators to estimate the total loads from polluted overflows during a typical year. Herrmann et al. (1999a) found that the discharge of urea, which hydrolyzes to ammonia with a corresponding increase in pH, could cause fish toxicity after a CSO event. The concentration of ammonia plus urea in the combined sewer discharge was found to be a more relevant measure of the likelihood of a fish kill after an overflow event than the concentration of ammonia alone. Saul et al. (1999) investigated the production of undesirable solids in combined sewer flows as it related to social, economic and ethnic factors. The goals of the research were first to determine the differences in the characteristics of the solids in the sewers that were ultimately discharged to the receiving water and then to use the solids' characteristics to predict the efficiency of CSO treatment devices, especially CSO chambers. St. Michelbach and Brombach (1999) showed that the nutrient content, especially of dissolved phosphorus, from CSO and existing wastewater treatment plants (WWTP) was endangering the health of Lake Constance. They proposed a simple methodology to estimate the nutrient loads from CSO to the Lake, the results of which can be used to determine the cost-effectiveness of CSO improvement versus WWTP improvement.

Fish and macroinvertebrate sampling defined and prioritized the needs of CSO systems and assessed where other watershed pollutants caused more harm than CSO (Markowitz, 1998).

CE-QUAL-W2 was used to determine the impacts of CSO during a four-year study to mathematically model the water quality of Cheatham Lake on the Cumberland River below Nashville, Tenn. (Adams *et al.*, 1997).

Mulliss *et al.* (1996) found that several wet-weather flow (WWF) discharge parameters regularly pose a serious threat with regard to freshwater aquatic life. Widera and Podraza (1996) investigated instream biological conditions and water quality during 52 CSO events in three years in a small stream near Essen, Germany. Notable observations were that ammonium concentrations increased by up to 70 times during CSO discharges, protozoa counts were significantly higher downstream of the CSO, while macroinvertebrate counts showed little difference. However, the composition of the aquatic-life communities differed substantially between upstream and downstream locations, showing that common ecological indices (such as the index of diversity) are not suitable tools for detecting these changes because they do not correctly reflect the differences in community structure.

The main impact of a CSO is generally a decreased level of oxygen in the receiving waters, according to Seidl *et al.* (1996). An extensive monitoring program in a Paris, France suburb to measure the bacteria and organic carbon content of a combined sewer under both wet- and dry-weather conditions in order to more accurately predict the resulting dissolved-oxygen (DO) conditions was conducted. Lammersen (1996) examined DO and ammonia (NH₃) conditions in receiving waters affected by stormwater in northern Germany. No events during a three-year-monitoring period were found to have caused critical conditions for these two parameters. Brosnan and O'Shea (1996) reported on the decrease in coliform bacteria concentrations in the receiving waters of New York's Hudson-Raritan Estuary. Among the contributors to this water-quality improvement is the increased capture of wet-weather CSOs.

Risk Assessment

The Office of Water at EPA (1999) published *CSO: Guidance for Monitoring and Modeling* as a reference for persons and institutions involved in evaluating the effects of CSO on all users of an impacted receiving water. Bickford *et al.* (1999) reported on the methodology developed and implemented by Sydney Water to assess the risk to humans and aquatic organisms in creeks, rivers, estuaries and ocean waters from WWF. The model used in this study was designed to predict concentrations of various chemicals in WWFs and compare the values to toxicity reference values. Brent and Herricks (1999) proposed a methodology for predicting and quantifying the toxic response of aquatic systems to brief exposures to pollutants such as the contaminants contained in stormwater runoff. The method contains an event-focused toxicity method, a test metric (ETU, event toxicity unit) to represent the toxicity of intermittent events, and an event-based index that would describe the acute toxicity of this brief exposure. The toxicity metric proposed (PE-LET50 [post-exposure lethal exposure time]) was the exposure duration required to kill 50% of the population during a pre-specified, post-exposure monitoring period. Colford *et al.* (1999) proposed three methods of analytically evaluating the impact of storm sewer and combined sewer outflows on public health, especially in areas that may receive through deposition the harmful agents in sewage and combined sewage. In the Puget Sound region of the U.S. Pacific Northwest, Greenberg *et al.* (1999) developed and evaluated the Urban Stream Baseline Evaluation Method to characterize baseline habitat conditions for salmonids. The methodology, based on assessment of geomorphic suitability, fish distribution and habitat alteration, was recommended for use to prioritize recovery actions. Stewart *et al.* (1999) collected diatoms (*Bacillariophyta*) and water quality samples from three streams that drain the Great Marsh in the Indiana Dunes National Lakeshore. They found that diatom species diversity could be used as indicators of water quality, which could then be linked to land use in a watershed. Diatom species diversity was most variable in areas with poorer water quality and was directly correlated to the total alkalinity, total hardness and specific conductance of the water in the stream.

Easton *et al.* (1999a and 1999b) presented the first phase of a project for determining the risk associated with human contact with waters contaminated with sewage-borne pathogens. Determination of the survival rates for these pathogens has been found to be crucial for determining the length of time after a contamination episode that the water was unsafe for human contact such as wading, swimming, etc. Die-off rate studies for total coliforms, *E. coli* (including *E. coli* 0157:H7), *Enterococci*, and *Giardia lamblia* were performed in situ in a stream known to have SSO. The survival rates, when combined with local hydrologic data, would be used to predict fate and transport of these microorganisms. Wakeham (1999) reported on the results of the investigation to determine why an \$800 million investment program designed to improve swimming water quality in the northwest coast of England was not effective. They found that the problem of compliance with water quality criteria for human exposure to pathogens was more complex than originally

believed and that current data analysis techniques and models by themselves could not completely described the complex environment.

Groundwater Impact

According to research by Dale et al. (2000), urban runoff, in addition to leaking underground fuel storage tanks and pipelines, has been shown to transport methyl tert-butyl ether (MTBE), a fuel oxygenate, to groundwater supplies. A survey performed by the authors also demonstrated that personal watercraft that use fuel containing MTBE is another potential source of MTBE to surface waters and groundwater. Di Carlo and Fuentes (2000) investigated the potential in Florida for monosodium methanearsonate (MSMA) to be transported to the groundwater after its application on golf courses. The results of their modeling showed that the unconfined Biscayne Aquifer was susceptible to MSMA and arsenate contamination. Uddin (2000) reported on the deterioration of groundwater in Malaysia due to agriculture, and industrial and human activities. The results showed that phenolic compounds, coliforms, iron, manganese and mercury had the highest frequencies of exceeding water quality standards. The water quality studies performed by Thomas (2000) indicated that the shallow groundwater near Detroit, Michigan, had higher median concentrations of nitrate, chloride and dissolved solids in areas with residential development. These groundwaters appeared to be impacted greatest by septic tank effluent in urban stormwater infiltration, especially runoff from paved surfaces. Zobrist et al. (2000) investigated the potential of using roof runoff for groundwater infiltration/recharge. The authors found that a first flush of pollutants was seen from the inclined tile and inclined polyester roofs and that corrosion of drains released copper in sufficient quantities to potentially damage the groundwater and surface receiving waters.

Standish-Lee (2000) reviewed the work performed by the Palmdale (California) Water District as part of their Wellhead Protection Plan. This project determined that the groundwater supply was most vulnerable to leaking septic tanks, illegal activities/dumping, trunk sewer lines, US Air Force Plant 42, dry wells, gas stations, junk/scrap yards and leaking underground storage tanks. Other locations of groundwater contamination sources included stormwater runoff detention basins, highways, railroads, golf courses, housing developments, hardware stores and repair shops. Stuurman (2000) outlined the Netherlands "National Groundwater Flow Systems Analysis (NGFSA)" project, which was designed to map the regional groundwater flow system and the associated groundwater/surface water interactions. The purpose of this project was to provide this information for urban planners in order to prevent the water systems from being stressed by drought, flooding, and/or pollution.

NPS contamination of surface and groundwater resources with nitrate-N ($\text{NO}_3\text{-N}$) has been linked to agriculture across the midwestern United States (Cambardella et al., 1999). Moorman et al. (1999) reported that herbicide, mainly atrazine and metribuzin, transport in subsurface drainage and shallow groundwater can result in unacceptable levels of contamination in surface waters. An investigation of the Walnut Creek watershed, California was performed to characterize the geology, groundwater flow, and water quality in geological units impacted by agriculture (Eidem et al., 1999). The infiltration of dissolved herbicides and metabolites from a tributary stream can occur where the stream crosses a floodplain overlying an alluvial aquifer causing the contamination of shallow alluvial aquifers at rates that exceed in-field leaching by up to three orders of magnitude (Burkart et al., 1999).

Hatfield et al. (1999) examined a multi-disciplinary study on the effect of farming practices on subsurface drainage, surface runoff, stream discharge, groundwater, volatilization, and soil processes that influence water quality. Groundwater was vulnerable to contamination in karst areas where highway stormwater runoff may flow directly into karst aquifers with little or no natural attenuation and transport highway-derived contaminants rapidly from sinkholes to locations in the aquifer. Field testing sites were located in Knoxville, Tennessee and Frederick, Maryland. A pilot-scale stormwater runoff treatment system, in Knoxville (Tennessee) and Frederick (Maryland), has been designed using peat, sand, and rock to remove contaminants by sedimentation, filtration, and adsorption prior to groundwater recharge.

Control of stormwater in sinkhole areas of Springfield, Missouri has involved the utilization of several standard approaches: concrete-lined channels draining into sinkholes; installation of drainage pipes into the sinkhole "eyes" (swallow holes); filling of sinkholes; elaborate drains or pumps to remove stormwater from one sinkhole and discharging into another drainage basin or sinkhole; and enlargement of swallow holes by excavation to increase drainage capacity. Three sites were analyzed to examine the effectiveness of contrasting design approaches to stormwater management. These sites differ in vegetation, on-site/off-site considerations, and types of development proposed (Barner, 1999). Since little was known about the influence of microorganisms which develop in urban stormwater infiltration basins on the transfer of heavy metals. Herbard and Delolme (1999) examined the transfer of zinc solutions (2-20 ppm) at different pH (4-7) by columns of sterile sand or sand colonized with *Pseudomonas putida*. By the analysis of the observed time series

of streamflow from catchments, the main components of the underlying groundwater balance, namely, discharge, evapotranspiration loss, storage and recharge, can be identified and quantified. This holistic estimation method was demonstrated for the Harris River catchment in southwest Western Australia (Wittenberg and Sivapalan, 1999).

Fan and Bras (1998) presented an analytical solution to a hillslope-based formulation of subsurface storm flow and saturation overland flow (Suzuki et al., 1998) examined pesticide concentrations in groundwater and in water leaching from a golf course in Japan and found that the golf course represented an area of high pollution potential compared to agricultural land. Their study emphasized the need to examine subsurface drainage in addition to runoff water when examining pesticide transport from golf courses. The relationship between stormwater and shallow groundwater in urban areas was evaluated (Lopes and Bender, 1998). Urban land surfaces were found to be the primary NPS of most VOC, with urban air being a secondary source. Using oxygen and deuterium isotopes, Iqbal (1998) traced the sources of storm runoff in a watershed in Iowa. The isotopes determined the relative contributions to river flow from rainwater and from ground water which had been flushed from the soil by infiltrating stormwater. The feasibility analysis of a simulation system to assess the impact on groundwater of various hypothetical situations (in the field of water management, land use, etc.) focused on the infiltration of stormwater in a periurban environment and involved space and time scales that apply to mid- and long-term management of groundwater resources (Bernard and Miramond, 1998).

Barrett and Charbeneau (1997) studied the impact of an urban watershed contributing recharge to the Barton Springs and Edwards Karst Aquifer in Austin, Tex. Results indicated that changes in N concentration in the aquifer would not be noticeable. Garrett and Petersen (1997) developed a series of lakes at Green Valley Park for both groundwater recharges and stormwater management in Payson, Ariz.

One of the major concerns of stormwater infiltration is the question of adversely impacting groundwater quality. Pitt *et al.* (1996a) reviewed many studies that investigated groundwater contamination from stormwater infiltration. A methodology was developed to evaluate the potential of stormwater contamination and it was concluded that there is only minimal potential of contaminating groundwaters from residential-area stormwaters (chlorides in northern areas remains a concern).

Planned groundwater recharge

Dillon et al. (1999) reported on the use of storage aquifers under urban areas to enhance groundwater recharge and to decrease the volume of surface runoff and combined sewer effluent reaching the receiving waters. Similarly, Lin et al. (1999) discussed the use of reclaimed wastewater plus stormwater to recharge the groundwater in the Caprock Aquifer in Oahu, Hawaii. Munevar and Marino (1999) developed a model for evaluating the artificial recharge potential on alluvial fans in the Salinas Valley in California. They found that average recharge/infiltration rates ranged between 0.84 and 1.54 cm/hr and that recharge efficiency ranged from 51 to 79%. Their model results demonstrated that planned recharge and streamflow augmentation could significantly reduce the groundwater overdraft and seawater intrusion in the area. Shentsis et al. (1999) reported on the transmission losses and groundwater recharge, including transmission losses from the vadose zone, from rainfall-runoff events in a wadi in Israel. They found that, during large events, evaporation was substantially smaller than the losses. However, in general, the annual recharge was very small, while losses were on the same order of magnitude as the stream flow. Wittenburg and Sivapalan (1999) used streamflow recession analysis and baseflow separation to quantify the components of the groundwater, i.e., discharge, evaporation losses, storage and recharge. Groundwater evaporation through water uptake by trees biased the recession curve. Data analysis of the data, stratified by time of the year, allowed the evaporation loss to be quantified as a function of time of the year and the used groundwater storage.

Generally, igneous and metamorphic rocks have been considered to be barriers to groundwater flow, while carbonates were assumed to allow flow through their fractures. Thyne et al. (1999) found, however, recharge occurring in the Indian Wells Valley through flow in a fractured bedrock that was originally thought to be impermeable. Their results demonstrated that using surface topography along with a knowledge of the location of the bedrock to estimate groundwater flow quantity and direction may not be suitable.

Chemical groundwater impacts

Barraud et al. (1999) reported on the quality of the groundwater below two infiltration sites in urban areas of France. Kayabali et al. (1999) investigated the chemical contamination of the groundwater in alluvial aquifers adjacent to Ankara Creek since it was believed that Ankara Creek pollution was contaminating the local groundwater. However, it was determined, using analysis of basic ions, organics and metals, that Ankara Creek was not responsible for groundwater

contamination, partly because a blanket of fine sediment in the bottom of the creek was expected to adsorb pollutants and to reduce infiltration rates. Lerner et al. (1999) combined a water balance with multiple solute balances to model the flow of water and chemicals into the groundwater under Nottingham, UK. They found that sewers contributed only about 13% of the total nitrogen loading, while leaking drinking water mains was about 36% of the total. The remaining 50% of the nitrogen loading came from parks, gardens, landfills and industrial spillages. Reddy (1999) reviewed the available data from public water suppliers in Wyoming which use groundwater. Nitrate and pesticides were two of the most frequently detected contaminants in groundwater and two of the most frequently detected pesticides were aldicarb and atrazine. Groundwater contamination was found to be a problem especially in areas that were heavily agricultural. Stephenson et al. (1999) investigated the impact of highway stormwater runoff flowing through a karst area and found that little to no attenuation of the runoff pollutants occurred. For most of the contaminants analyzed, the peak loadings arrived at the groundwater table and at the spring it recharges approximately one hour after they were found in the sinkhole that received the highway drainage. Nowicki et al. (1999) found that denitrification of groundwater was not significant in a well-oxygenated vadose zone and aquifer. Denitrification was found to occur to a greater extent in the estuary which receives the groundwater.

Lin et al. (1999) used the boron isotope ratio to trace reclaimed wastewater in a directly recharged aquifer on the Island of Oahu in Hawaii. They also investigated other tracers, such as chloride and silica, and found that, because of the influence of seawater, they were not suitable tracers for the reclaimed water. The results of this study were used in conjunction with mixing curves to determine the fraction of reclaimed water in a well and could be used to calibrate or modify fate and transport models for this aquifer with regard to other pollutants in the recharged water. Mengis et al. (1999) used nitrate-to-chloride ion ratios, concentrations of 15-Nitrogen and 18-Oxygen and an in-situ nitrate/15-N tracer experiment to investigate whether nitrate was being attenuated in the vadose zone and/or the aquifer below a riparian zone. Their results confirmed that denitrification rates could be measured in situ using this procedure. They also confirmed that this methodology could distinguish between water being recharged from the riparian zone versus that being recharged from irrigation of the nearby agricultural fields.

The Technical University of Denmark (Mikkelsen *et al.*, 1996c and 1996d) has been involved in a series of tests to examine the effects of stormwater infiltration on soil and groundwater quality. It was found that heavy metals and PAHs present little groundwater-contamination threat if surface infiltration systems are used. However, concern was expressed about pesticides which are much more mobile. Squillace *et al.* (1996) along with Zogorski *et al.* (1996) presented information concerning stormwater and its potential as a source of groundwater MTBE contamination. Mull (1996) stated that vehicular-traffic areas are the third most significant source of groundwater contamination in Germany (after abandoned industrial sites and leaky sewers). The most significant contaminants are chlorinated hydrocarbons, sulfate, organic compounds, and nitrates. Heavy metals are generally not significant groundwater contaminants because of their affinity for soils. Trauth and Xanthopoulos (1996) examined the long-term trends in groundwater quality at Karlsruhe, Germany. It was found that the urban-land use is having a long-term influence on the groundwater quality. The concentration of many pollutants have increased by about 30-40% over 20 years. Hütter and Remmler (1996) described a groundwater-monitoring plan including monitoring wells that were established during the construction of an infiltration trench for stormwater disposal in Dortmund, Germany. The worst-case problem expected is with zinc, if the infiltration water has a pH value of approximately 4.

Microbiological groundwater impacts

Barrett et al. (1999) suggested the use of chemical and biological markers for identification of urban groundwater recharge sources. Their paper documented only the sewage 'fingerprint,' a combination of stable nitrogen isotopes and microorganisms. Trihalomethanes had been proposed as a marker for leaks in the drinking water mains, but they were not found in sufficient quantity in the drinking water itself to be an effective measure of groundwater contamination. Markers were not presented for precipitation.

Soil application was proposed as a means of disposal of propylene glycol-based aircraft deicing fluids (ADF). ADF biodegradation was investigated by Bausmith and Neufeld (1999) and the results showed that biodegradation of solutions of less than 20% by weight ADF could be degraded in the soil profile prior to reaching the groundwater. Hebrard and Delolme (1999) investigated the ability of the soil to adsorb the zinc from the infiltration water. Their work showed that the adsorption of zinc retarded the arrival of zinc to the groundwater. Adsorption was found to be reversible except at pH 6 and 7 and was found to be non-instantaneous. These results demonstrated that contact time and conditions control the amount of biofilm removal and retention of zinc from percolation water. Degradation of the groundwater by human and animal excrement was documented by Buckles et al. (1999) for an area in Ecuador where the groundwater table was rising. The degradation of the groundwater in combination with the rising water table produced swamp-like conditions

where the water and land were not suitable even for subsistence farming.

Decision-Support Systems

Numerical Models

Many enhancements have been made to the EPA SWMM model since the last official EPA release in 1994 (Huber et al. 2000). These have included improvements to the model engine, enhancements to input/output options, and “hooks” for easier interfacing with graphical user interfaces and ancillary software. The U.S. EPA Office of Research and Development (ORD) Urban Watershed Management Branch (UWMB) has identified two major objectives for urban modeling research: to develop a standard operating procedure for the user community, and to develop a BASINS-compatible SWMM – GIS interface (Koustas 2000). Koustas provided the SWMM-user community with a description of the UWMB approach to urban watershed modeling research and provided an update on ORD SWMM-related projects.

Distributed models were more and more used in regional hydrology. One of the main reasons was their essential compatibility with raster data in Geographical Information Systems. Zech and Escarmelle (1999) investigated the possibility of using other kinds of databases designed more specifically for cartography. Casser and Verworm (1999) described the upgrading of the existing hydrodynamic rainfall runoff model HYSTEM/EXTRAN and the decision finding model INTL for real time performance, their implementation on a network of UNIX stations and the experiences from running them within an urban drainage real time control project. The main focus was not on what the models do but how they were put into action and made to run smoothly embedded in all the processes necessary in operational real time control.

Modelers were often faced with data gaps and other problems which may not even come to light until well into the modeling process. Greer (1999) addressed these issues in the context of a case study of a watershed management project conducted in Silver Lake Watershed in central Delaware. A suite of hydrologic, sewer system and riverine water quality models have been used to address technical questions that have been asked in Rouge River Watershed (Michigan) planning (Kluitenberg et al., 1999).

Zug et al. (1999) described modeling efforts to address both flood control and pollution prevention at Gentilly, France. A mathematical model was satisfactorily calibrated and validated and was now being used to simulate the operation of the catchment area and its associated sewerage system.

Schlater and Koehler (1998) asserted that expectations between owner and consultant regarding model applicability and associated development cost are misaligned and that matter-of-fact information concerning what a typical model can and cannot do needs to be clear in the minds of both parties. A checklist is provided to address what an owner needs to know about model development but does not know how to ask. Ahyerre et al. (1998) examined stormwater runoff quality models to determine why no model has achieved widespread use and indicate that the generation and transport of polluted runoff in an urban setting is complex, involves many media and many time and space scales, which renders stormwater quality models difficult and expensive to utilize. The authors suggested that a clear distinction should be made between management tools and research models. Gaume et al. (1998) studied the estimation and interpretation of the parameter uncertainties of conceptual models used in hydrology using a global approach. They concluded that the lack of measured data and its relative redundancy cause a significant interaction between the parameters which hinders calibration and that the data available in hydrology are only sufficient to support the development of models with limited complexity.

The Stormwater and Water Quality Management Modeling Conference, held in Toronto, Ont., Can. in February 1996 yielded a collection of articles which addressed a wide range of modeling applications for WWF impacts management. This accumulation of articles is the fifth in a series of monographs published and includes presented information on methods for urban- watershed management and planning; modeling stormwater quality; storage and treatment practices; and a stormwater-system evaluation (James, 1997).

Within the United States, users continue to rely on existing urban-stormwater models. TenBroek and Brink (1996) compared several continuous-stormwater-simulation models including STORM and SWMM. Donigian *et al.* (1996) compared the attributes of six urban- and seven nonurban-stormwater models. Mercer *et al.* (1996) summarized the use of a variety of stormwater models including SWMM, WASP, the Watershed Management Model, and P8 as part of the Rouge Project in the Detroit, MI area. Donahue *et al.* (1996) summarized the use of modeling and evaluation tools to select a cost-effective CSO-control plan within a watershed perspective. The attributes of six stormwater models are compared by Shoemaker *et al.* (1996). Swarner and Thompson (1996) presented the results of extensive measurements

and modeling of SSO problems in Seattle, WA. The results of an extensive SSO evaluation using XP SWMM for the Miami, FL sewer system are described by Walch *et al.* (1996). Kachalsky *et al.* (1996) described modeling and evaluation methods of optimizing CSO control in New York, NY. Herrmann and Klaus (1996) did general water and nutrient budgets for urban-water systems including stormwater.

A variety of international urban-stormwater models have been released in recent years. Neylen *et al.* (1996) described the first version of the HydroWorks-stormwater-quality-management model being developed by Wallingford Software in the United Kingdom. Foller *et al.* (1996) showed how MOUSE can be used to optimize a combined-sewer system in East Germany. Dempsey *et al.* (1996) described SIMPOL, a simplified urban-pollution-modeling tool developed as part of the United Kingdom's Urban Pollution Management Research Program. SIMPOL models the stormwater system as series of tanks. Bente and Schilling (1996) proposed an object-oriented approach for an urban-hydrologic-simulation system. Davies (1996) discussed the importance of the appropriate blend of modeling and data for SSO evaluations including a discussion of the advantages and disadvantages of SWMM and HydroWorks. A very extensive evaluation of the Sydney, Australia SSO problem was done with MOUSENAM and SEEKER to simulate and optimize control options (Hayes, 1996). Ji *et al.* (1996) describe a fast model for evaluating the hydraulics of sewers and open channels. This work showed the implicit-solution scheme in the SUPERLINK model to be much faster than EXTRAN's explicit solution. Gent *et al.* (1996) surveyed models that can simulate solid deposition and resuspension in sewers. MOUSETRAP and HydroWorks QM that supersedes WALLRUS and MOSQUITO were described. Jack *et al.* (1996) described several models for characterizing sewer sediments. Brief descriptions of the WALLRUS/HydroWorks PM hydraulics model, the STOAT wastewater-treatment-performance model, and the MOSQUITO, HydroWorks-DM and MOUSETRAP sewer-flow-water-quality models were provided. Imbe *et al.* (1996) used a water budget to establish the effect of urbanization on the hydrological cycle of a new development near Tokyo, Japan. This development is trying to reduce hydrologic impacts by encouraging infiltration systems and storing rainwater. Mitchell *et al.* (1996) described a water-budget approach to integrated-water management in Australia. Budgeting is done at the individual parcel, neighborhood, and wider catchment scale. A current gap in urban stormwater modeling is the inability to properly incorporate the impact of rainfall on frozen surfaces in urban areas. Thorolfsson and Brandt (1996) described Norwegian experience in which "worst case" conditions occur during these winter periods. The development of new mathematical models to handle this special case were recommended.

Model Applications

An integrated system in Flanders consisting of a sewer, a wastewater treatment plant and a river component was selected for a modelling project (Fronteau and Bauwens 1999). The purpose of that project was to assess the impact of CSO on the receiving water and to investigate on the effects of different operating scenarios within the sewer system. Commercial mathematical models were used, i.e. both the sewer network and the WWTP were modelled with Kosim, while Isis was used to represent the river system. An overview of extended stormwater treatment alternatives is discussed and as well as the possibility of including these practices in simulation models (Mehler and Ostrowski, 1998).

Watanabe *et al.* (1999a) described a distributed simulation model of water quality and stormwater runoff, which can simulate both open-channel and surcharged flows and at a temporal and spatial variation of runoff-water quality in the pipe systems. The proposed model consists of two models: one was PWRI (the Public Works Research Institute, the Ministry of Construction, Japan) Model for water quality simulations; the other was the SLOT Model for stormwater runoff simulations.

The distributed parameter (grid cell) agricultural nonpoint source runoff (AGNPS) model compared stormwater-runoff volumes, flowrates, and sediment loads from a forested watershed and urbanized watershed for ten simulated rainfall events and included the effects of impervious surfaces on runoff and sediment transport. The rainfall volume to runoff volume ratio was 14.5% higher in the urban watershed with the maximum differences occurring at rainfall depths < 75 mm (Corbett *et al.*, 1997). A complex watershed-scale water-quality-simulation model, the Hydrological Simulation Program-FORTRAN (HSPF) model, was calibrated for a 16 km² catchment. It was necessary to apply a critical process that included sensitivity analysis, numerical optimization, and testing of derived-model-parameter sets to evaluate their performance for periods other than those for which they were determined (Jacomino and Fields, 1997). Runoff depth and pollutant loadings for BOD, SS, Total Kjeldahl Nitrogen (TKN) and Pb computations, respectively for four small sites (i.e., 14.7 acres — 58.3 acres) in South Florida were respectively performed using the Soil Conservation Service (SCS) hydrology method and empirical equations developed by the U.S. EPA. Comparisons of predicted versus measured data for both hydrographs and pollutant loadings were reported (Tsihrintzis and Hamid, 1997). The Extended Transport block (EXTRAN) of the Storm Water Management Model (SWMM) Version IV was modified to include the effect of variable

roughness for circular pipes on routed hydrograph attenuation and lag time (Zaghloul, 1997). Routing simulations using variable roughness resulted in hydrographs with significant peak-flow attenuation and lag time.

Rainfall variability and effects on modeling.

The National Weather Service's WSR-88D radar (NEXRAD) was used to estimate the spatial distribution of rainfall for three storms over the Brays Bayou watershed in Houston for hydrologic modeling purposes (Bedient et al. 2000). The results from the radar proved to be as accurate, and in some cases more accurate, than the rain gauge model when predicting runoff volume, peak flow, and peak time. Chan (2000) explored the spectral behavior of rainfall of various temporal resolutions and presented a method of generating rainfall data that combined the approaches of stochastic modeling with a disaggregation goal. The total rainfall volumes of the generated data compared well with observed values but tended to produce lower rainfall intensities and longer rainfall durations per event.

Sempere-Torres et al. (1999) presented a case study where the use of rainfall estimates from weather radar pictures was compared with the use of a rain-gauge network in terms of the ability to predict sewer flows in an urban basin in Barcelona, Spain. The results showed that the use of radar data enables the combined sewer systems model to better simulate observed flows, and provide support for the idea that the spatial description of rainfall was a key problem in modeling the events giving rise to CSO.

Luk et al. (1999) described a rainfall forecasting model that integrates an artificial neural network (ANN) with a GIS. The ANN was trained to recognize historical rainfall patterns recorded from a number of gauge of the study catchment and to make point forecasts of rainfall. The GIS was used to spatially distribute the point rainfall forecasts produced by the ANN. Mikkelsen et al. (1999) used regional modeling of a range of rainfall variable statistics to assess the performance of different historical rain time series. Sufficiently long rain series were rarely available from the exact catchment in question and for this reason simulations were often based on available rain series from other locations. Nnadi et al. (1999) tested the ability of various design storm distributions to simulate the actual rainfall pattern and to compare the runoff rates used in the design of stormwater management devices in the State of Florida using continuous simulation. Peak-runoff rates from design storms based on the various distributions were compared to those that would result from actual rainfall events. The results show that the behavior of the design storm distributions varies across the state.

Willems (1999) reported on data collected from a dense network of rain-gauges in Antwerp, Belgium to study the stochastic structure of spatial rainfall at the small spatial scale of small hydrographic or urban catchments. The derived spatial rainfall model contains two structures: a deterministic structure for the physical description of individual rain cells and cell clusters, and a stochastic structure for the description of the intrinsic randomness in the sequence of different rain events. Durrans et al. (1999) compared a number of approaches to the problem of how to disaggregate rainfall time series using polynomial approximating functions. Results of these evaluations indicate that a disaggregation method presented by Ormsbee was a relatively good performer when storm durations were short (2 h), and that a quadratic spline-based approach was a good choice for longer-duration storms. Most hydrologic/water quality (H/WQ) models that use rainfall as input assume spatial homogeneity of rainfall. Under this assumption this study assesses the variability induced in calibrated model parameters solely due to rainfall spatial variability. A large uncertainty in estimated model parameters could be expected if detailed variations in the input rainfall were not taken into account (Chaubey et al., 1999).

Useful variables for defining the state and evolution of a rain system include rainfall rate, vertically integrated rainwater content and advection velocity. The forecast model proposed in this work complements recent dynamical formulations by focusing on a formulation incorporating these variables using volumetric radar data to define the model state variables, determining the rainfall source term directly from multi-scan radar data, explicitly accounting for orographic enhancement, and explicitly incorporating the dynamical model components in an advection-diffusion scheme. An evaluation of this model was presented for four rain events collected in the south of France and in the northeast of Italy (Dolcine et al., 1999). A procedure to generate rainfall input for the EUROpean Soil Erosion Model was presented. To develop such a procedure, first of all the influence of rainfall event amount, rainfall event duration, and time to peak intensity of event rainfall on soil losses, calculated with EUROSEM, has been tested for several rainfall stations. It seems possible to produce site specific appropriate rainfall input for EUROSEM, only with the knowledge of distributions for the investigated basic rainfall parameters; however, to improve the procedure and make it practically useful, it will be necessary to account for seasonal changes of distributions of basic rainfall event parameters (Strauss et al., 1999).

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contains two structures: a deterministic structure for the physical description of individual rain cells and cell clusters, and a stochastic structure for the description of the intrinsic randomness in the sequence of different rain events. Such a model forms the basis of the stochastic generation of spatial rainfall for urban catchments (Willems, 1999). Gyasi-Agyei and Willgoose (1999) presented a generalized hybrid model to generate point rainfall for a wide range of aggregation levels. The rainfall process was expressed as a product of a binary chain model which preserves the dry and wet sequences as well as the mean, and a correlated jitter, a second-order autoregressive Gaussian process, used to improve the deficiencies in the second-order properties of the binary chain. Two possible binary chain models were analysed, a non-randomized Bartlett-Lewis model and a Markov chain.

Daily rainfall records for durations of 30, 20, 10, 5, 4, 3, 2, and 1 years from six stations were analyzed revealing positive evidence of the existence of chaotic behavior in daily rainfall data for Singapore (Sivakumar et al., 1998). Results also suggested that the attractor dimensions of rainfall data of longer time periods are higher than that of shorter time periods. DeGaetano (1998) developed a clustering algorithm to form regions with similar extreme rainfall cumulative distribution function (CDF) characteristics and applied it to extreme rainfall data from W.V. Lambert and Kuczera (1998) modeled interstorm and storm durations for several Australian state capitals, illustrated practical issues in calibration and identification, and concluded that a generalized exponential model can replace 12 monthly models to describe the seasonal stochastic variation of interstorm time. Data from four rain gauge stations were analyzed by the fuzzy mode recognition method. The distributive character of a rainfall pattern for a short duration storm was given and the design-storm pattern was satisfied for the urban drainage by simulation and comparison (Cen et al., 1998).

Hromadka (1997) used a set of realizations of error data from rainfall-runoff hydrological models and generated a set of error transfer function realizations to equate to the original data using a four-section algorithm. Fernando and Jayawardena (1998) used artificial neural networks (ANN) to model the rainfall-runoff process. The radial basis function type of ANN saved considerable modeling time and effort.

Rainfall-runoff quantity models.

The Hydrologic Modeling System (HEC-HMS) is “next generation” software for precipitation-runoff simulation and will supersede the HEC-1 Flood Hydrograph Package. The program is a significant advancement over HEC-1 in terms of both hydrologic engineering and computer science (Scharffenberg and Feldman 2000). Current capabilities of the HEC-HMS program that are not found in HEC-1 are discussed. Nguyen et al. (2000a) applied two different optimization methods to calibrate the RUNOFF block of the SWMM model: the Downhill Simplex Method, and the Shuffled Complex Evolution (SCE) Approach. Better results were found using the SCE approach. A semi-distributed conceptual rainfall-runoff model for urban catchments was developed (Aronica and Cannarozzo 2000). The urban drainage network was idealized as a cascade of non-linear cells with kinematic wave routing. The results indicated that both the variation in the spatial representation of the rainfall and the variation in the spatial discretization of the catchment influence the outlet hydrographs.

New developments in information technology were proposed to estimate spatially variable parameters for hydrologic simulation systems (Ball 2000c and 2000d). Control parameter estimation philosophies were discussed, and techniques were demonstrated on the use of hydroinformatic systems in parameter estimation. The development of urban databases provided a convenient means of accessing information for the purpose of hydrological modeling (Rodriguez et al. 2000a). A recently developed model, ‘SURF’ (semi-urbanized runoff flow), was specifically designed to couple with a GIS. SURF was evaluated with a 7-year continuous data series and was shown to compare favorably to both measured data and results from URBAN, another urban hydrologic model.

Hydrologic losses were estimated on the basis of rainfall-runoff data recorded in 21 urban experimental catchments (Becciu and Paoletti 2000). From analysis of experimental data, the probability distribution function of the runoff coefficient was found to be approximately normal, and simple relationships for estimation of main moments were developed. The impact of grid-cell size on calibrated parameters and on the performance of a variable source area model intended for urbanizing catchments was examined by modifying TOPMODEL concepts to accommodate urban surfaces (Valeo and Moin 2000a). Results showed that in this integrated model of urban and rural areas, predicted processes based on calibrated parameters were dependent on grid resolution. The snow accumulation and melt routines of three drainage models that have been applied to urban settings were reviewed; two of these, MouseNAM and SWMM, were designed for urbanized catchments; the third, HBV, was a regional-scale model for rural catchments (Semádeni-Davies 2000). All contained a temperature index for melt – this method is shown to be theoretically unsound without modification for urban simulations. Literature on model development, validation, and application was found to be lacking.

In many cities of the world, urban cells may be hydraulically defined where built-up areas are highly subpartitioned into walled properties (Hicks et al. 2000). A method was proposed to quantify flood damage vulnerability based on hydraulic properties of the urban cell and on peak flow and time to peak. A flood inundation model was developed by combining a SWMM-based model of a storm sewer network and a two-dimensional (2D) overland-flow model (Hsu et al. 2000). SWMM was employed to solve the storm sewer flow component and to provide the surcharged flow hydrographs for surface runoff exceeding the capacity of the storm sewers.

The Object Watershed Link Simulation (OWLS) model was developed and used to simulate the hydrological processes within the BBWM. The OWLS model was a three-dimensional, vector-based, visualized, physically-based, distributed watershed hydrologic model. Simulation results provided a close examination of hydrologic processes of flow separations and Variable Source Areas (Chen and Beschta, 1999).

Donnelly-Makowecki et al. (1999) examined whether the quasi-distributed response function used in TOPMODEL provides superior performance for event simulation in small, temperate forested catchments, compared to lumped reservoir representations of runoff routing similar to those employed in many catchment hydrology models. The alternatives were a two-reservoir black-box model and a three-reservoir model structured to represent our perceptual model of runoff processes based on held observations. A second objective was to test the statistical significance of differences in model performance using a new approach that combines the Jackknife with analysis of variance (ANOVA).

A procedure was introduced for applying the statistical approach to water-table management models, e.g., DRAINMOD, a H/WQ model used to simulate lateral and deep seepage through the soil profile. In the evaluation procedure, probability distribution functions were developed for the most sensitive input parameters, output probability distribution functions were developed using Monte-Carlo simulation, and the output probability distribution functions were used to assess the model. DRAINMOD performed successfully in the evaluative procedure in predicting the runoff, subsurface drainage volume, and the water-table depth fluctuations, which were expected to be most susceptible to input uncertainty (Sabbagh and Fox, 1999).

Matheussen and Thorolfsson (1999) presented research on the simulation errors due to insufficient temporal resolution in urban snowmelt models. Storm-sewer overflow was calculated from an artificial overflow for all time resolution. Based on this research, the authors propose that snowmelt-produced runoff in urban areas should be measured and modeled with no more than a 1-hour time resolution.

Vertessy and Elsenbeer (1999) described a process-based storm-flow generation model, Topog SBM consisting of a simple bucket model for soil water accounting, a one-dimensional kinematic wave overland flow scheme, and a contour-based element network for routing surface and subsurface flows. Aside from topographic data and rainfall the model has only six input parameters: soil depth, saturated hydraulic conductivity at the soil surface, the rate of decay of saturated hydraulic conductivity at the soil surface with depth, the Manning surface roughness parameter, the maximum (saturated) soil water content, and the minimum (residual) soil water content. The model was applied to La Cuenca, a very small rainforest catchment in western Amazonia that has been well characterized in several hydrometric and hydrochemical investigations.

Ando et al. (1999) described how the effects of urbanization on the hydrological water cycle were estimated by using a simulation model to quantify the constituent elements of the hydrological-water cycle. A questionnaire survey was conducted among residents of the river basin to identify the problems that the residents wish to have resolved through the restoration of the hydrological-water cycle in the Azuma River and to set target values for the desired improvements. Becker et al. (1999) presented a few examples where detailed field studies described the essential elements of runoff generation and thus help to achieve a more realistic representation of the underlying mechanisms within process-oriented rainfall-runoff models.

An approach was developed for incorporating the uncertainty of parameters for estimating runoff in the design of polder systems in ungaged watersheds. Monte-Carlos simulation was used to derive a set of realizations of streamflow hydrographs for a given design rainstorm using the SCS unit hydrograph model. This approach was demonstrated for the Pluit Polder flood protection system for the City of Jakarta, Indonesia. Although, the SCS model was limited to agricultural conditions, the approach presented herein may be applied to other flood control systems if appropriate storm-runoff models were selected (Yulianti and Lence, 1999).

A modified Rational Formula approach for designing urban storm sewer systems included the conventional detention pond and the double detention pond (Wu et al., 1998). This approach also estimated the hydrographs which may be applied to design the conventional detention pond or the double detention pond with results showing the double can hold up to 50% of the volume compared to the conventional. The calibration of the Soil Conservation Service (SCS) runoff equation using rainfall and runoff data from six storms in Fla. showed that the CN for impervious surfaces may differ from the value of 98 suggested by SCS, and in warm climates may be closer to 94 or 95 (Pandit and Regan, 1998). Due to the nonlinear behavior of sewer systems, hydrodynamic simulations using single storm events often do not lead to a good probability estimation of the overflows. Well calibrated, simplified models using long-time simulations give better results (Vaes and Berlamont, 1998). Guo and Adams (1998) derived closed-form analytical expressions for average annual runoff volume and runoff event volume return period based on an equation which describes the rainfall-runoff transformation on an event basis, and the exponential probability density functions of rainfall event characteristics. Guo and Adams (1998) also derived analytical expressions or probabilistic models for peak discharge rates that are proposed as an alternative to simulation modeling or regional analyses for the determination of flood frequencies for urban catchments.

Hromadka and Whitley (1999) developed a mathematical formalization of link-node hydrologic models using HEC-1. By subdividing a watershed into numerous subareas, and connecting the subareas by a network of links, a link-node model representation of the watershed was constructed. King et al. (1999) compared two methods of simulating excess rainfall on a large basin with multiple rain gages. The SCS daily curve number method (CN) was compared with the Green-Ampt, Mein-Larson (GAML) method on the Goodwin Creek Watershed. Li and Joksimovic (1999) presented a methodology to define the average conditions for urban drainage system modelling. The drainage system performance should be first analyzed in a cursory manner to identify the average conditions and the "typical rainfall year". A detailed analysis of the drainage system performance should then be conducted for the "average rainfall year" and the "typical rainfall year." If the discrepancy in performance was large, the "typical rainfall year" should be used in the analysis of average conditions of urban drainage systems. Loke et al. (1999) compared Artificial Neural Networks (ANN) and Grey-Box Models (GBM), implementing them in three practical urban storm drainage case studies. The advantages of ANN included good generalization, high fault tolerance, high execution speed, and the ability to adapt automatically without human intervention. However, ANN relied strongly on the availability of data examples, and they were not transparent and obstruct any direct analysis and interpretation of their performance. On this basis the GBM was superior, as it enables the user to get a better insight into the involved uncertainties. Mehlhorn and Leibundgut (1999) discussed the use of tracer time parameters to calibrate the baseflow time of concentration in a conceptual rainfall-runoff model. A comparison showed that the modeling approaches in tracer hydrology and rainfall-runoff modeling were mathematically equivalent. Therefore, it was assumed that tracer time parameters were suitable to calibrate baseflow runoff models. Coupling water age and turnover time made it possible to simulate the baseflow in more detail.

Milina et al. (1999) showed that, for Norwegian cities, large flood events have only been affected to a minor degree by urban development whereas short-term events occurring after dry-weather conditions show a significant increase in runoff. The effects of urbanization on runoff have been studied where many catchments have yielded maximum flow from autumn and winter frontal rains, often concurrent with snowmelt or rain on frozen ground. Morita and Yen (1999) presented further developments of the conjunctive urban runoff model and focus on the interaction between surface and subsurface flow components. This interaction was directly related to the estimation of effective rainfall or initial loss of hyetographs. The model reproduced the initiation of overland flow and initial loss process and enables the estimation of the effective rainfall reasonably and theoretically.

Nania et al. (1999) designed and conducted experiments on flow patterns at street crossings and intersections. A one-dimensional formulation was proposed in order to predict the dividing flow in street crossings. Rigby et al. (1999) developed a sophisticated event based urban hydrology model from very simple beginnings. It highlighted the capabilities of earlier models and how they have increased in complexity and functionality over the last two decades. Shen et al. (1999) proposed the fuzzy neural network model called "FUZZY STORMNET" to estimate volumetric flow from rainfall intensity. This model for flow estimation could be calibrated automatically by use of known storm events, and no knowledge on the field and the sewer system was needed. Smith (1999) presented a decision support system for drainage engineers involved in the design of stormwater management facilities. The runoff model was versatile and involved a variety of methods for storm description, rainfall loss estimation and overland flow routing. In addition to normal pipe and channel sizing, the design options include a number of detention devices for on-site controls such as rooftop and parking lot storage, in-line storage super-pipes and exfiltration trenches. Stephens and Kuczera (1999) tested the widely

used time-area method at the parcel scale. The time of concentration for impervious areas at the allotment scale was found to be of the order of 2 min and not the 5 min as assumed in Australian practice. This result has implications for the design of sub-catchment scale pipes, storage basins and outflow control devices.

Terayama (1999) developed a stormwater runoff model based on the modified Road Research Laboratory method, to express the effects of on-site storage considering temporary storage of the effective rainfall and its disposal. An example application of this model in a local city, which has introduced the on-site storage facilities, was also presented. A nonlinear rainfall-runoff model was developed and applied to flood runoff analysis in Japan. Sugiyama et al. (1999) extended the model's applicability by developing practical equations for estimating model parameters that were appropriate on a regional basis. The utility of the estimating equations was tested by computing runoff hydrographs for lumped basins. Vaes and Berlamont (1999) showed that a well-calibrated reservoir model can predict CSO emissions as well as a detailed hydrodynamic model, taking into account the uncertainties in the input data. Such simplified models were ideal tools to perform quickly various scenario analyses. Physically based conceptual models give an optimal balance between model uncertainty and uncertainty in the input data.

Wong and Kho (1999) studied the increase of flood peaks due to urbanization. Four urbanization scenarios were simulated and subjected to the Singapore 2-year rainfall. The degree of urbanization was expressed in terms of the percentage of developed area and the percentage of channelized area. Their results showed that the patterns of the flood peak increase for the downstream to upstream and the inside to outside urbanization sequences were concave. Wong and Li (1999) reported on a conceptual study of the hydrological effects of urbanization. By considering urbanization on an overland plane as a process whereby a relatively rough, permeable surface was gradually replaced by a relatively smooth, less permeable surface, the effect of urbanization sequence on the flood peak was theoretically assessed by the kinematic wave method.

Yen et al. (1999) presented details of the runoff model ILUCAT. The model allowed temporally variable rainfall in incremental times as input to each catchment, and deducts abstractions to yield the rainfall excess to be routed through the urban catchment. Each catchment was divided into five types of areas, namely, direct impervious, direct pervious, supplemental impervious, supplemental pervious, and noncontributing areas. The rain excess was routed through two flow paths of the first four contributing areas using the time-area method to produce the runoff hydrograph. Cagiao et al. (1999) presented two different methodologies for a study of the runoff generated in an urban watershed with a separate sewer system during stormwater events. The first approach used a process simulator (SWMM), and a non-linear parameter estimation tool (PEST), while the second used artificial neural networks. A pilot project of a subcatchment in the city of Santiago de Compostela was studied. Campolo et al. (1999) used neural networks to forecast flow rates in the Arno River downstream of the city of Florence, Italy during low-flow conditions. The model used basin-averaged rainfall measurements, water level, and hydropower production data. Model predictions were found to be accurate with root-mean-square error on the predicted river flow rate, less than 8% over the entire time horizon of prediction. Chang and Hwang (1999) used the group method of data handling (GMDH) algorithm to evaluate complex rainfall-runoff processes in a heterogeneous watershed in Taiwan. Two versions of the revised GMDH model were implemented: a stepwise regression procedure and a recursive formula. The prediction results of the revised GMDH models and the instantaneous unit hydrograph (IUH) model were compared. Much better performance was obtained with the revised GMDH models.

Dinicola (1999) presented recent efforts to develop regionalized HSPF parameters for King and Snohomish Counties in Washington that were useful for urbanizing watersheds. Djordjevic et al. (1999) described a model for dual drainage - an approach to rainfall runoff simulation in which the numerical model takes into account not only the flow through the sewer system, but also the flow on the surface. The numerical model simultaneously handled the full dynamic equations of flow through the sewer system and simplified equations of the surface flow. The surface excess water (due to the limited capacity of inlets or to the hydraulic head in the sewer system reaching the ground level) was routed to the neighbor subcatchment (not necessarily the one attached to the downstream network node), using surface retentions, if any. Edijatno et al. (1999) described a new empirical watershed model that involves only three free parameters. In spite of its crude simplicity, it achieved, on average, worthwhile results on a set of 140 French catchments and overwhelmingly outperformed a linear model involving 16 parameters. It performed roughly as well as a conceptual model with five free parameters, derived from the well-known TOPMODEL.

Escameia and Swaffield (1999) summarized the results of research on monitoring and modeling stormwater runoff from roofs in the UK. This paper presented important new data for the design of rainwater systems and concludes that numerical simulations of unsteady flows were a useful tool for complementing the design recommendations in current

design guides. Four simple conceptual daily rainfall-runoff models were applied to a 25-basin data set in the UK, covering a range of sizes, topographies, soils and climates (Houghton-Carr, 1999). Model performance was judged by a range of quantitative and qualitative measures of fit, applied to both the calibration and validation periods. These included efficiency, mean annual runoff, baseflow index, the synthetic monthly and daily flow regimes, and the flow duration curve. With increases in computing power of recent years, fully two dimensional, unsteady hydraulic modelling was becoming increasingly common for applications involving large, complex floodplains. Bishop *et al.* (1999) described the results of a recent study of a highly urbanized area along the Gold Coast, Queensland, Australia. With the increasing focus on ecologically sustainable development, and concerns regarding class actions by flood affected communities, many agencies in Australia were requiring that new proposed urban development have zero impact. With regard to flooding impacts, this requirement has resulted in the need for assessment of effects, in terms of water level changes, down to 1 cm or less accuracy. Details were provided on the requirements of and approach to full two dimensional flow modelling including the required grid definition and size, structure modelling, fine scale nesting and model stability and accuracy (Collins *et al.*, 1999). A distributed, field-based rainfall-runoff model was developed for the 1400-km² arid catchment of Nahal Zin, Israel. No calibration with measured flow data was performed; the model used rainfall radar input applied over a catchment that was spatially disaggregated into different terrain types according to hydrologically relevant surface characteristics. In general, this study showed that field-based data on generation and losses of runoff may be incorporated into a distributed hydrologic model to overcome calibration with the poor data records of arid high-magnitude events (Lange *et al.*, 1999).

Miles *et al.* (1999) presented a method of analyzing flow and rainfall monitoring data that has successfully documented rainfall dependent infiltration and inflow (RDI/I) reduction in Charlotte, North Carolina and Greenville, South Carolina. The method relies on scientific principles including good data quality control practices and the use of control areas to establish changes in RDI/I between monitoring periods because of environmental factors. Schultz *et al.* (1999) summarized research, conducted by a team of consultants and cooperating municipal agencies, which identified and tested eight major categories of rainfall derived infiltration and inflow (RDII) analysis methods in several diverse sewersheds. They identified metrics suitable for objective comparison of the RDII analyses, and concluded with recommendations for selecting RDII methods appropriate to a variety of applications. In the Netherlands, a very simple criterion for flooding was used to check the hydraulic behavior of a drainage system, whereas The European approach was more strict but not applicable. Therefore, van Luijcklaar (1999) presented an alternative approach to eliminate hydraulic bottlenecks in drainage systems in flat and moderately sloped areas.

A topographic index predicted patterns of runoff, reproduced spatial patterns of subsurface-storm flow for a variety of prestorm conditions, and was used as a basis for a rainfall-runoff model (Woods *et al.*, 1997). Three conceptual rainfall-runoff models (i.e., GSF, IHACRES, and LASCAM) were assessed and provided accurate predictions of rainfall-runoff relationships (Ye *et al.*, 1997). Tan *et al.* (1997) developed an algorithm for simulating tropical rainfall using a one-step-Markov-chain model. The results indicated that the synthetic-rainfall time series reproduces the characteristics of tropical rainfall. The model may also be capable of estimating extreme-annual rainfall. A geomorphology-based-unit hydrograph and a Runge-Kutta-time-discrete scheme were applied to predict direct-runoff volumes. The hydraulic-routing scheme presented was highly accurate in predicting runoff volumes and may be useful in managing major-rainfall storms (Sepulveda, 1997).

Nine flood-estimation models used for ungauged-urban watersheds were evaluated in Louisiana. Flood-quantile predictions from simple regression models calibrated by local data were found to be more reliable than those more complicated models or models with many parameters that may not be accurately estimated (Yu and Adrian, 1997). A newly digitized record of precipitation for 304 sites in the Midwest United States that extends back to 1901 challenged the the assumption that extreme-rainfall time series are stationary and without trends. It was suggested that rainfall-frequency studies be updated on a regular basis for maximum usefulness because of observed changes in the annual maximum time series (Angel and Huff, 1997).

Hydrological studies of rainfall-runoff processes provided the basis for estimating design flows for urban-stormwater-drainage systems which control floods and the transport of sediments and pollutants. Oloughlin *et al.* (1997) summarized the theory of urban rainfall-runoff processes, the development of modeling practice, and the current use of computer models. Agbodo *et al.* (1997) reviewed HYDRA, HydroWorks, MOUSE, and XP-SWMM, which are widely used hydraulic-modeling tools utilized in determining optimum improvements of sanitary-sewer systems that have excessive I/I. Zhu and Schilling (1997) presented a method to predict errors of calculated mean-annual-overflow volume due to coarse temporal resolution of rainfall data that was used as input to rainfall-runoff models. Errors were quantified by

comparison of overflow volumes based on rain-data series with different temporal resolution. The pattern of the temporal rainfall variation of the two data series were too different to derive error-prediction rules that were generally applicable for all rainfall regimes.

Rainfall-runoff quality models.

The results of a number of investigations indicated that contaminant transport should consider the speciation of nutrients and metals in stormwater runoff (Ball 2000c). From the results of these studies, a new approach for the simulation of contaminant transport was presented which considers the speciation of the contaminants. Statistical models were proposed to predict the total mass of specific pollutants removed with stormwater runoff from an urban residential catchment (LeBoutillier et al. 2000). The models were based on analysis of data collected during an on-going research program in Saskatchewan. A method for predicting the thermal enhancement of stormwater runoff from paved surfaces was documented for a test facility in Kingston, Ontario, Canada (Van Buren et al. 2000b). Prediction of runoff temperature was based on TRMPAVE, a mathematical model that was developed using a thermal energy balance approach and the one-dimensional heat equation to predict the surface temperature and temperature gradient in asphalt during dry-weather and wet-weather periods. An export coefficient modeling approach was used to assess the influence of land use on phosphorus loading to a Southern Ontario stream (Winter and Duthie 2000). It was found that runoff from urban areas contributed most to the loading of phosphorus to the stream. An existing model of sediment wash-off from paved surfaces was extended to predict fine granular sediment inputs into drainage systems via roadside gully-pots (Deletic et al. 2000). The model was applied to two catchments in Dundee, Scotland where it was concluded that only two calibration parameters are required to estimate the input of fine granular sediment into storm drainage systems via gully-pots.

Tsanis (2000) developed a program named RUNMEAN (RUNOffMEAN) for estimating toxic-contaminant event mean concentrations (EMCs) in stormwater runoff.

Bent et al. (1999) evaluated the runoff and erosion response of two perennial grass species on simulated waste burial covers at Idaho National Engineering and Environmental Laboratory. The Agricultural Non-Point Source Model (AGNPS) permits the incorporation of important spatial information (soils, landuse, topography, hydrology) in simulating surface hydrology and NPS runoff. The AGNPS model was adapted for developed coastal watersheds by deriving urban coefficients that reflect urban landuse classes and the amount of impervious surface area (Choi and Blood, 1999).

Skipworth et al. (1999) described an experimental model investigating erosion and subsequent sediment transport of an in-pipe, fine-grained, organic, cohesive-like sediment deposit analogous to those found in sewers. The problem of optimal water distribution to a range of retention reservoirs in an urban sewer network during rainfall events was overflows and its impact on receiving waters. A multilayer control structure consisting of an adaptation, an optimization, and a direct control layer, was proposed for the solution of this complex problem (Marinaki et al., 1999). Watershed areas that generate NPS polluted runoff need to be identified prior to the design of basinwide water projects. The model TOPLATS simulates variable source area (VSA) hydrology and therefore provides an improvement to the current generation of NPS models for locating potential NPS-loading areas (Endreny and Wood, 1999).

Arnbjerg-Nielsen et al. (1999) compared trends in annual loads of pollutants to receiving waters in Denmark during the past decade. For N and COD, models were suggested that explain some of the variation between and during events. However, a large residual variation was identified and possible refinements of the model were discussed. Ball (1999) presented a new approach for simulation of the transport of the soluble contaminant in urban stormwater runoff. This modeling system was based on a decoupled solution of the kinematic wave equations for simulation of the surface flows and an advection-diffusion model for simulation of the contaminant motion. Use of deicing chemicals and abrasives to provide traffic safety during winter caused water quality problems for urban receiving waters (Bartosova and Novotny, 1999). Their model was calibrated using data from the Lincoln Creek watershed (Milwaukee, Wisconsin), and verified on 30th Avenue watershed (Edmonton, Alberta). The results of simulation for chlorides, suspended solids, and lead were presented.

Carr et al. (1999) discussed the benefits of a time series approach which provided the information necessary for design of water quality control structures and for assessment of ecological sustainability. An advantage of the time series approach was that it provides an integrated evaluation of performance during a variety of wet-weather conditions. Chiew and McMahon (1999) presented a simple approach for estimating long-term runoff and diffuse pollution loads in urban catchments, and discussed conceptual modeling methods for simulating daily runoff and pollution loads. The modeling results for several catchments in Australian capital cities were presented. The study indicated that long-term and daily

runoff can be estimated reasonably accurately using simple approaches. However, the water quality characteristic can vary considerably between catchments.

Commonly measured fecal bacteria concentrations in water and rainfall data were utilized as inputs for training a neural network model to distinguish between urban and agricultural fecal contamination present in inputs to a drinking water reservoir (Brion and Lingireddy, 1999). A neural network model was written that used bacterial and weather data to differentiate between three site classifications: urban, agricultural and a mixture. The validity of the source identification, neural network model was verified through a case study. Roadside gully pots form a common and important part of many surface water drainage networks (Butler and Mernon, 1999). Their primary function was to retain larger solids from road runoff in order to minimize the problems associated with sediment deposition in downstream drainage structures and receiving waters. A dynamic water quality model has been developed to simulate these processes. Moulton et al. (1999) described NPDES monitoring for New Orleans, Louisiana. This paper asked the question, "How reliable were load estimates that were extrapolated from landuse based monitoring of small subcatchments?" The age of the developed areas was found to be responsible for differences in monitored nutrient loading from modeled runoff loads based on land use.

Several models related land use categories of urban, forest, agriculture, and wetland to in-stream concentrations of total nitrogen (N) and total P in eight low-order watersheds on the coastal plain of S.C. (Tufford et al., 1998). The models with highest predictive strength were those which used land closest to the stream channel. Vezjak et al. (1998) modeled the effects of eutrophication on plankton seasonal dynamics in lakes using state variables for the rates of change of phytoplankton, zooplankton, N and P. The influence of P concentration on eutrophication was one of the most important processes in the lake ecosystem. Bartolini et al. (1998) stressed the need for a complete rainfall-runoff model of the rainfall-runoff transformation that includes the underground portion of the hydrograph even if the maximum discharge during a flood is mainly due to the surface runoff. The proposed solution, taking into account the unknown time-lag between rainfalls and discharges as an extra parameter to be estimated in the calibration phase showed some benefits. An examination of several models for estimating stormwater pollutant loads from urban watersheds indicated that SS loads are largely a function of runoff volume, and that the use of a single event- mean concentration of SS for all urban land uses provided reasonable estimates of stormwater pollutant loads. Water quality data did not indicate a strong correlation between pollutant loads in runoff and the duration of the antecedent dry period (Charbeneau and Barrett, 1998).

The response of rain on ammonium loads for an urban sewer system using AQUASIM and MOUSE TRAP 3.0 was simulated. The study showed that a sewage storage tank performed better for the integrated load discharged into the system but a combined sewer storage tank would be more efficient in decreasing peak values and the duration of high concentrations in the river (Holzer and Krebs, 1998). A semi-empirical model quantified the hysteresis of river water constituents during a storm based on discharge data collected from several river sites over a storm hydrograph. Results showed that most constituents had higher concentrations during the rising limb of the hydrograph and lower concentrations during the falling limb (House and Warwick, 1998). The COD of a sewer network was modeled using a ratio of COD/SS as a function of the maximum rainfall intensity over a five minute period, SS and time. Simultaneous measurements of rainfall, hydraulics, SS and COD in three catchments with different characteristics and not used in the calibration phase validated the model (Zug et al., 1998). Osuch-Pajdzinska and Zawilski (1998) presented the results of calibration and verification of mathematical models for calculating hydrographs and pollutographs of urban stormwater based on results obtained from field studies for a mixed industrial and residential catchment. Tsihrintzis and Sidan (1998a) calibrated and verified the Santa Barbara Method for computing runoff hydrographs for small urban watersheds. The PC version of ILLUDAS was shown to predict hydrographs that compared well with measured hydrographs for small urban watersheds in Fla. (Tsihrintzis and Sidan, 1998b).

Mas (1998) used a relatively simplistic modeling approach to quantify the stormwater impacts of a proposed commercial development in southern N. Engl. A ten-year simulation assessed the impact of current and future nutrient loads and sediment runoff to a multipurpose reservoir scheduled to open in 1999 in Sarpy County, Nebr. and recommended BMP (Fowler et al., 1998). Brown et al. (1998) examined the interactions of land use, topography, soil, and surface water hydrology in modeling stormwater quality variations in subbasins of the Tijuana River watershed. Concentrations in Onondaga Lake, N.Y. of total Hg and MMHg in the water column, sediments and fish tissue are elevated due to industrial inputs, wastewater discharge and urban runoff. The steady-state Regional Mercury Cycling Model suggested that elimination of Hg inputs from wastewater effluent and drainage from a former chlor-alkali facility would decrease Hg concentrations in fish tissue (Gbondo-Tugbawa and Driscoll, 1998).

The South Africa Water Research Commission funded a project to adopt an existing urban-stormwater-runoff model to data from several catchments and showed that urban-stormwater runoff was highly polluted with nutrients, heavy metals, organics, and bacteria (Water Qual. Int., 1997a).

The spatial distribution of the water-quality equivalent of a snow cover on various landscapes were synthesized through log-normal distributions to predict snowmelt and runoff (Shook and Gray, 1997). When snow produces a significant portion of runoff, a smaller number of quality records could be more valuable for modeling than a much larger number of records of lower quality because the overall value of an operational-hydrometeorological network depends on the consistency and representativeness of average conditions of the collected records (Peck, 1997).

Collection system, CSO and SSO models.

An abatement strategy was developed for three CSO outfalls in the Bronx, New York (Brilhante, et al. 2000). EPA SWMM was used along with cost and receiving water quality modeling to define the optimal level of in-line storage required to meet regulatory requirements. To achieve desired CSO control for the City of Edmonton's Gold Bar Wastewater Treatment Plant (GBWWTP), the hydraulic relationship between the upstream collection system and the GBWWTP was evaluated by including a detailed hydraulic model of the treatment plant as part of the collection system hydraulic model (Gray et al. 2000). This study provided details on the approach used to simulate these two system components in an integrated model. Hydraulic/hydrologic modeling was conducted using the EPA SWMM model in support of the design of a CSO consolidation/ relocation project in South Boston (Walker et al. 2000b). Findings indicated that an original facilities planning model was reasonably accurate in predicting peak flows in extreme storm events, despite only being calibrated to a 3-month storm.

The U.S. EPA is in the final stage of issuing an SSO Rule that will add control of SSOs to the NPDES permit requirements (Lai et al. 2000). This paper provided a preview of the rule and described the advantages of employing a modeling approach for capacity assurance of various components of a collection system and development of an SSO mitigation plan.

The City of Columbus Inflow and Infiltration Program utilized a comprehensive sewer system evaluation and hydraulic modeling approach to mitigate sanitary sewer overflow and water-in-basement occurrences (Chase et al. 2000). By identifying problems in the collection system and incorporating them into a hydraulic model prior to SSO mitigation alternatives analysis, the City of Columbus will be able to target capital improvement and maintenance dollars to correct the problems in the collection system and reduce SSOs. The Miami-Dade Water and Sewer Department used wet weather data from a supervisory Control and Data Acquisition telemetry system to quantify rainfall dependent infiltration and inflow (RDII) (Christ et al. 2000). The MS Access application developed to quantify the individual pump station's RDII response is discussed in this paper. A detailed computer model of the Metropolitan Sewerage District of Buncombe County, North Carolina collection system was used to identify collection system improvement alternatives (Harris 2000). Alternatives included strategic application of sewer rehabilitation and upgrades, off-line storage and additional treatment capacity. The Encina Wastewater Authority developed a Peak Flow Management Plan, in which effluent equalization storage as an alternative to a new ocean outfall was evaluated using a risk-based approach (Hogan et al. 2000). A continuous simulation model of wet weather flows and storage/outfall facilities was used to generate estimates of peak flows, storage volume requirements, and project costs over a range of return periods.

A global mathematical model for simultaneously obtaining the optimal layout and design of urban drainage systems for foul sewage and stormwater was presented (Diogo et al. 2000). The global strategy adopted combined dynamic programming and metaheuristics to develop a sequence of optimal design and plan layout subproblems. A computational method for the optimal design of highway drainage inlets was formulated as a discrete-time optimal control problem (Nicklow and Hellman 2000). The example revealed that genetic algorithms and the discrete-time optimal control methodology comprised a comprehensive decision-making mechanism that could be used for cost-effective design of storm water inlets.

The FORTRAN source code in EXTRAN block of SWMM has been modified to take advantage of parallel processing for faster program execution (Burgess et al. 2000). Reductions in run times exceeding 30% were achieved. SWEHYDRO and MOUSE were combined to model both the collection and treatment system for Edmonton, Alberta (Ward et al. 2000). A detailed simulation of the treatment plant hydraulics was performed to optimize its operation during wet weather periods.

The pros and cons of design storm and continuous simulation techniques were compared for treatment plant and collection system design purposes (Dent et al. 2000). Examples were included from several municipal master-planning studies that illustrated how results can vary from one approach to another. The shear stress distribution over the sediment bed in a pipe with deposited sediments was quite uniform but larger than the mean shear stress in the cross section (Berlamont et al. 2000). Comparisons between numerical calculations and (unsteady) sediment transport measurements confirmed these results qualitatively.

Modeling and analysis of combined sewer systems received considerable attention. Milina et al. (1999) described the development of an integrated model and its application to the Hovringen wastewater system in Trondheim, Norway. The model integrates sewage production, transport and treatment simulation, the interface with existing databases and the simulation of processes that were controlled in real time, and has been used to design the treatment process as well as static and dynamic measures in both the catchment and the sewer system. Krebs et al., (1999) use measurements and numerical simulations to show that the first flush effect may cause a significant impact on the receiving water when CSO occurs, or on a wastewater treatment plant when the sewer network was flat and catchment area was large. Alvarez et al. (1999) analyzed, from an environmental point of view, the structural and functional scheme considered for the sewage management of a small coastal community in the Bay of Biscay in Spain, where the presence of overflows in the system during storms leads to the release of a great deal of pollutants.

Furumai et al. (1999) applied a distributed model to study the reduction of CSO pollution for a combined sewer system in Japan, which contains a storage pipe with 3 weirs for inundation control. Results indicate that the model can be applied for evaluating effectiveness of modified operation or new installation in the sewer system for suspended sediment load reductions, once initial conditions on surface deposits and sediments were properly determined. Grum and Alderink (1999) performed a return period analysis of CSO effects using embedded Monte-Carlo simulations, putting all quantities described by probability distribution in either an inner layer consisting of quantities varying from event to event or an outer layer consisting of uncertain but constant quantities. This resulted in a band of return period curves representing the return period distribution for which confidence limits may be calculated. Jack et al. (1999) described a study which utilized detailed simulation models of the sewerage and treatment plant performance for the City of Perth in Scotland in order to investigate the potential problems caused by introducing system storage to control both flooding and polluting spills. The Jefferson County, Alabama Environmental Services Department was currently implementing a program to address the need for collection system rehabilitation and capacity improvements in its wastewater collection systems, and Keckley (1999) discussed the use of an extensive network of flow monitors and rain gauges in each collection system to assess the extent of needed capacity improvements as well as the impact of rehabilitation. Milina et al. (1999) described some results of an integrated model development and its application to the Hovringen wastewater system in Trondheim, Norway. The developed integrated model has been used to design, in both the catchment and the sewer system, the treatment process as well as static and dynamic measures including extended pumping, adjustment of overflows, separation of stormwater runoff from "non-effective separate systems", retention and real-time control of the sewer tunnel volume.

The local Water Authorities of the Basque Country (Spain) have adopted an integrated model for the design of the sewer system of this community. The model was developed specifically for the study of coastal sewerage under dominant wet weather conditions. It includes: (1) Establishment of the site specific statutory requirements and environmental objectives, (2) Design of sewer system components with specific reference to influences on marine water quality, and (3) Development of monitoring programs (Alvarez et al., 1999).

Aronica (1999) presented a simple numerical model based on the method of continuity for flood routing in urban networks. The network was represented as a cascade of cells and the flood routing was schematized as a flux transfer between adjacent cells. Preliminary tests were carried out by means of the reproduction of flood wave propagation for some examples of urban drainage systems, both hypothetical and real. The results showed satisfactory numerical stability and an excellent computational efficiency. Barnett and MacMurray (1999) stressed the importance of correctly modeling overland secondary flow paths. At drainage network nodes such as street intersections, the distribution of outflow depends on nodal compatibility conditions, particularly when one or more of the outflow paths was steep, and large errors accumulated from the application of incorrect conditions at a succession of nodes.

Welker et al. (1999) investigated possible changes to quantity and composition of sewage in the combined sewer system and the WWTP caused by new stormwater management strategies (mainly by disconnecting areas from the sewer system). Various scenarios were developed and the consequences on the water systems were calculated by using the

simulation model KOSMO, in a fictional catchment.

The Monte-Carlo simulation approach was demonstrated in an integrated setting involving models for rainfall characteristics, CSO loads and impacts on the surface water DO. CSO loads were modeled using event lumped non-linear regression models with rainfall as input and with overflow volume, duration and relevant event mean concentrations as output; oxygen depletion in the surface water was described using a dynamic model including oxidation of dissolved COD and nitrification. The parameters of all the models were estimated from observed data on rainfall, CSO load and surface water impacts (Grum and Aalderink, 1999).

Ideta and Kariya (1999) used hydraulic simulation to maximize inline storage and reduce flooding. Kleckley (1999) described estimating sanitary sewer system surcharging during wet weather using measured rainfall and flow. A rainfall-peak flow relationship was developed and used to analyze capacity improvements and the impact of rehabilitation on peak rates. This method should not be used exclusively as it does not assess the impact of rehabilitation on high groundwater infiltration. Lorenz and Weikopf (1999) presented a form of combined sewerage network storage management called the cascade technique. This technique utilized fully adjustable weirs to dynamically control the flow in the sewerage system. The cascade technique can be seen as an approach to decrease both the water pollution and the investment and operation costs caused by combined sewerage systems. Maitland et al. (1999) presented new features of XP-SWMM32, a model for complex open and closed conduit drainage systems. The application of these new and existing features of the XP-SWMM32 package to real-world drainage problems was outlined through the presentation of several case studies of representative drainage systems in the United States, Japan, and Australia.

Merlein and Valentin (1999) investigated design features of sewer systems to increase the capacity of sewerage systems under pressurized flow. A mathematical model was used to compare the results of the hydraulic model under steady conditions with unsteady conditions as they were during a cloudburst.

Morrow (1999) outlined the hydraulic modeling requirements of a program to meet a new, demanding discharge consent standard (average of 3 spills per bathing season per outfall) at specific coastal discharge points. A program costing over \$105M had to be designed, approved by the regulator, procured, built, and commissioned in a period of 15 months. Continuous simulation was the only valid way of confidently establishing the additional storage volumes required to meet the new consents. Vazquez et al. (1999) proposed a new set of parameters for the Muskingum model for routing in a circular main in a sewer network for a wide range of lengths, slopes and diameters. A neural network was used to design the parameters of this model. This new application of Muskingum equations enables mean relative errors of less than 6% to be obtained for the value and the point in time of the flood in the case of mains up to 6500 m long, with slopes varying from 0.5% to 1% and with diameters ranging from 150 to 2000 mm.

Watanabe et al. (1999b) proposed a practical lumping method for manholes under surcharged flow, in which all the water surface areas of ignored manholes were preserved in the water surface areas of the adjacent manholes. The lumping method was applied to a combined sewer pipe system in Matsuyama City drainage basin in Japan and the adaptability of the method was investigated through stormwater runoff simulations. Wong et al. (1999) discussed the City of San Diego's (California) program for monitoring and modeling of its wastewater facilities. This sustainability concept had implications in terms of the databases, modeling tools, and applications of the model. Two key elements that were highlighted were the value of developing a custom GIS application to integrate and process data that was developed and updated by other City and County agencies, and applications of the model for both planning and operational studies that resulted in reduced capital and operating costs. During urban storms, the overloading of a sewer system or river bank overflow produced flows which were essentially routed by the road infrastructure and cause flooding of adjacent built-up areas (Hingray et al., 1999).

The evaluation of the damage suffered by these built-up areas required the determination of important hydraulic parameters of the inundation, such as the maximum water depth or the inundation duration. This paper described the hydraulic behavior of flooded built-up areas at different scales: individual plot, block of plots. Online sewer flow forecasting was simulated in this study using an autoregressive transfer function rainfall-runoff model and a recursive procedure for parameter estimation (Gelfan et al., 1999). Three recursive estimation algorithms were used: the time-invariant and time-varying versions of the recursive least-squares algorithm, and the Kalman filter interpretation of this algorithm. The sensitivity of the forecasting accuracy to the model order and to the initial conditions of the algorithm was studied using sewer flow data from the Milwaukee (Wisconsin) Metropolitan Sewerage District. In the UK, current river quality monitoring programs provide little information for management of CSO discharges, or objective assessment

of their pollution impact. Balmforth et al. (1999) described a methodology that uses existing river flow data, which was available at sub-catchment level in the UK, to identify intermittent discharges by a development of the unit hydrograph method, based on the hypothesis that intermittent discharges produce unit hydrographs that lie outside the 'normal' correlation between effective rainfall and surface runoff for a catchment.

The EPA and the Miami-Dade (Miami, Florida) Water and Sewer Department negotiated a Consent Decree settlement, which required them to undertake the installation and maintenance of a computerized collection and transmission system model. The "Virtual Dynamic Computer Model" has the ability to predict potential SSO resulting from peak flow conditions (Walch et al., 1999). The Metropolitan St. Louis Sewer District has responsibility for the management of stormwater drainage as well as conveyance and treatment of sanitary sewage within its boundaries. The Watershed Master Plan's hydrologic and hydraulic analyses were conducted using the SWMM (Miller and Loucks, 1999). The local Water Authorities of the Basque Country (Spain) have adopted an integrated model for the design of the sewer system of this community. The model was developed specifically for the study of coastal sewerage under dominant wet-weather conditions and includes: 1) establishment of the site specific statutory requirements and environmental objectives; 2) design of sewer system components with specific reference to influences on marine water quality; and 3) development of monitoring programs (Alvarez et al., 1999). Hsieh and Wang (1999) introduced a semi-distributed parallel surface rainfall-runoff conceptual model. To evaluate the adaptability of this model, three watersheds around the city of Taipei in Taiwan were chosen to test the effectiveness of the model.

Hvitved-Jacobsen et al. (1999) presented a conceptual model for wastewater quality changes during transport in sewer systems. Emphasis was on microbial transformations of heterotrophic biomass and soluble and particulate fractions of organic substrate; the inclusion of sulfate respiration in the model concept was outlined. The model was exemplified as a tool for evaluation of wastewater quality changes in an intercepting gravity sewer. The model concept was tested in gravity sewers as well as in pressure mains.

Schlutter (1999) presented a numerical model capable of simulating sediment transport in combined sewer systems. The main objectives were to model mass transport rates at the outlet from a catchment and at the same time obtaining qualitative information on erosion and deposition going on at different locations in the sewer system. An example was given of a calibration event from a case study. Vollertsen et al. (1999) reported on the biotransformation of wastewater particles with different settling velocities. This was based on analysis of long term oxygen uptake rate measurements and a conceptual model describing aerobic transformations of organic matter. No significant change in the biodegradability of wastewater particles with different settling velocities were found.

Yagi and Shiba (1999) used fuzzy logic control and genetic algorithms to achieve improved pump operations in a combined sewer pumping station. Current pump operations could be improved by adding sewer water quality to the input variables and to the fitness function; the improved operations can reduce not only floods in the drainage area but also pollutant loads discharged to the receiving waters. Zug et al. (1999a) presented a conceptual model for solid production and transfer in combined or separate sewerage systems called HORUS. The objective of this model was to reproduce the hydrographs, taking into account the characteristics of the catchment and the structure of the sewerage system. Simultaneous measurements of rainfall, hydraulic, TSS and COD concentrations on nine very different catchments and about one hundred rainfall events allowed a large range of validation which can be considered of good quality. Zug et al. (1999b) presented the results of a study whose objectives were the definition of the exceptional rain event compared to the capacity of the sewerage system and the development of recommendations for the design and operation of the sewerage system to efficiently manage most rainfall events. The measurements allowed the calibration and validation of a model (HYDROWORKS), which included hydraulics and masses of total suspended solids. Artina et al. (1999) showed the results obtained from the ongoing investigation in an experimental catchment in Bologna (Italy), monitored in order to acquire data on the pollutant loads entering the sewer network and then spilled to the receiving stream by some CSO. These data were being used to calibrate a detailed model for both the sewer system and the river reach. Skipworth et al. (1999) described an experimental model investigating erosion and subsequent sediment transport of an in-pipe, fine-grained, organic, cohesive-like sediment deposit analogous to those found in sewers.

The Metropolitan St. Louis Sewer District developed a computer model to improve the control of SSO which incorporated the system's physical features, dry-weather flow and WWF, and the impact of bypass flow on receiving waters (Moore et al., 1997). Gall et al. (1997) outlined a process-modeling and simulation program which is part of a pilot-scale study of satellite-treatment options for the control of CSO.

Three case studies (force main shut-down analysis, rehabilitation of gravity interceptors, and WWF diversion) demonstrated the benefits of using dynamic hydraulic modeling to improve the operation and maintenance of collection systems (Hwang *et al.*, 1997). A physical model and the HydroWorks model were used to balance hydraulic criteria for an inline-storage tunnel intended for multiple uses (e.g., the control of CSO and SSO; and the reduction of urban flooding) (Switalski *et al.*, 1997).

Arthur and Ashley (1997) proposed to estimate the extent to which sediment in transport near the bed of sewers contributes to the first foul-flush phenomena by describing the movement of a storm wave along a conceptual sewer length. Sweden and the Slovenian Republic have applied the computer model MIKE 11 HD to solve CSO pollution problems. The model provided solutions which would protect the countries' receiving waters (Water Qual. Int., 1997b).

Detroit, Mich. tested and modeled the primary and secondary capacities at their WWTP as part of their Long Term Control Plan (Lieberman *et al.*, 1997). They found that the maximum solids processing and storage capabilities are sufficient to handle additional CSO loads, thereby reducing the need for additional CSO facilities. Results using the Direct Random Search optimization technique, with the planning level model HIRATE as the simulator, are presented for one of the facilities investigated in the Greater Cincinnati, Ohio CSO program (Pisano and Hui, 1997). Houston, Tex. devised a proactive approach by providing adequate planning and design time and realistic construction schedules to correct future potential SSO problems (Kidder *et al.*, 1997). Flanders, Belg. conducted an experimental program to identify the important parameters for evaluating the impact of overflow events on receiving waters, improving the design of storage-sedimentation tanks and overflow structures, and improving the capability of numerical models to predict emissions from CSS (Berlamont *et al.*, 1997).

Ruan and Wiggers (1997a) investigated the application potentials of the methodology of time-series models for predicting some values related to CSO characteristics, e.g., CSO discharge and water level versus rainfall intensity, pollutant load versus CSO discharge, etc. *Sewsim*, a conceptual CSO-emission model was developed from *Matlab* and *Simulink* and can model rainfall-runoff, surface solids buildup and washoff, and sewer-sediment erosion and deposition. Some *Sewsim* simulation results predict pollution load of CSO more effectively than deterministic models (Ruan and Wiggers, 1997b). Physical theory was incorporated in a stochastic model of water level and particulate COD of a Dutch CSO. Results suggested that most of the deviation between model prediction and observation were due to sewer-system behavior, which is not explained by the model (Grum, 1997). The particle-tracking routine in the FLUENT computational-fluid-dynamics (CFD) software has been employed in the prediction of storage-chamber sedimentation efficiencies, which are influential in the management of CSO events. FLUENT was shown to be highly sensitive to the particle injection location but less sensitive to either the particle size or density (Stovin and Saul, 1997).

Worm and Carstensen (1997) applied a stochastic-modeling technique to analyze a subcatchment sewer system in Sydney, Aust.

Models of controls.

The micro- and macro-management of stormwater design was examined from a design engineer's viewpoint based upon the traditional establishment of design values and not just meeting regulatory edicts (Olenik, 1999). Software was discussed by Smith (1999) that provides a decision support system for drainage engineers involved in the design of stormwater management facilities. The program provides suggested design parameter values that the user can modify, test and accept. A special feature allows the output file from one design session to be used as input to automatically test the design for a different storm, test a change in catchment or design parameters or simply to complete a design in two or more sessions (Smith, 1999).

Hushka *et al.* (1997) applied AGNPS to estimate erosion and nutrient loadings to the Mirror Lake watershed in North Dakota from five different scenarios of land use and management practices. AGNPS was also applied to a 72,000 acre watershed in south-western North Dakota for simulating the water quality of runoff overflowing the dam and to investigate the lake's responses to eutrofication (Yoon and Disrud, 1997).

CSO and SSO control. Hrabak *et al.* (1999) use three-dimensional computational fluid-dynamic (CFD) models to simulate various complex sewer and CSO components including mixing tanks, sedimentation basins, clarifiers and contact tanks. The modeling was used in lieu of physical modeling to support design. Vaes *et al.* (1999) described a conceptual model of storage sedimentation basins based on uniform flow, but taking into account anomalies due to non-uniform flow and turbulence. These anomalies were based on experiments in a physical model and simulations using

CFD. This model can deal with time varying input and can be used for continuous simulations. Ta (1999) simulated the flow characteristics in a storm tank using CFD. The efficiency of the storm tank acting as a sedimentation basin to retain the suspended particle was evaluated using a dispersed phase model. A range of particle sizes was included to evaluate the sediment profile at the end of the storm event and the carry-over of suspended particles during the spill. Tyack and Fenner (1999) described a CFD model of a 1600 mm diameter prototype hydrodynamic separator. The result showed that the high vertical velocities within the device permit only particles with a high settling velocity to be removed, with the fine suspended solids (mostly organic) being passed forward for treatment in the WWTP.

Mathematical modeling efforts of Monroe County, N.Y. initially used in the 1970's for a CSO abatement program are being brought into use for current modeling applications in the 1990's (Matzat et al., 1998). The city of Columbus, Ohio conducted a study to upgrade a WPCP and the collection system which included WWF (Abdel-Latif et al., 1998). The comprehensive modeling approach optimized the capacity of the collection system and its relationship to the WPCP. The U.S. EPA and the Miami-Dade Water and Sewer Department in Fla. negotiated a consent decree settlement which required the installation and maintenance of a computerized collection and transmission system model. This model, the "Virtual Dynamic Computer Model" has the ability to predict potential SSO from peak flow conditions (Walch et al., 1998b). The system demonstrated its value in determining that \$20 million of proposed construction was unnecessary (Walch et al., 1998a).

A dynamic hydraulic model of the Baton Rouge, La. sanitary sewerage system was developed and calibrated against recorded flow and rainfall and a number of operational modifications and system augmentations were proposed to optimize the use of the tanks to reduce the frequency of SSO (Moody and Baldwin, 1998). Model construction included the development of Real Time Control (RTC) code to simulate the operation and performance of two major offline storage facilities during the recorded storm events. Three RTC simulations demonstrated that RTC provided an alternative to traditional approaches for handling WWF in separate sanitary sewers. The three simulations all met the specific constraints of the example sewer system, i.e., reduction in the number and volume of SSO without exceeding the existing pump station capacity at the drainage outlet (Pierce and Dillard, 1998). Costs for developing RTC for stormwater treatment range from \$0.055 to \$0.082 /L-yr (\$0.21 to \$0.31 /gal-yr) compared to the cost of building storage facilities for the equivalent CSO reduction which would cost between \$0.40 and \$0.53 /L-yr (\$1.50 and \$2.00 /gal-yr) (Agbodo and Nelson, 1998). Colas et al. (1998) presented the technological advances made in a five year R & D project in which methods, software and technology specifically designed for CSO control made RTC a more feasible and accessible solution.

Dorn and Miles (1997) developed a preliminary sanitary-sewer system improvement cost-estimating method by using the U.S. Army Corps of Engineers's Storage, Treatment, Overflow, Runoff Model (STORM) and U.S. EPA Needs Survey Database.

Pond treatment. XP-SWMM was used to evaluate the performance of a retention treatment facility in Oakland County, Michigan (Buchholz et al. 2000). The results showed the amount of storage that is necessary to reduce the number of overflow events by 30%. A two-dimensional, vertically averaged hydrodynamic model was adapted to predict the circulation and sedimentation patterns in stormwater detention ponds (Dewey et al. 2000). The performance of the model for a pond system in Toronto was presented. The Storage-Treatment block of SWMM was used to model the effectiveness of extended detention ponds (Newman et al. 2000b). The results showed much improved designs over using traditional methods. The Corrugated Steel Pipe Institute developed software for designing underground stormwater detention tanks (Finlay, 2000). Designers could use the program to quickly perform the calculations associated with the design of underground storage detention facilities. Analytical probabilistic models were applied to analyze the runoff quantity/quality control performance of various combinations of storage and treatment systems (Li and Adams 2000). These models provided closed-formed solutions of the performance equations that were efficient in both a conceptual and computational sense.

Ponce and Klabunde (1999) tested the feasibility of temporarily holding stormwater in parking lots by using a diffusion wave model of catchment dynamics. Four extreme storm types were applied to four typical parking lot sizes to assess the sensitivity of the resulting storm hydrograph to the choice of design slope. Results show the promise of parking lot storage in urban stormwater management. Ristenpart (1999) presented detailed information about a new stormwater management concept. Dimensioning and proof of performance of the different drainage structures was carried out with the help of an innovative rainfall-runoff model that was also briefly described.

Zheng and Baetz (1999) investigated a range of suburban development alternatives from an urban hydrology perspective. An analysis of design scenarios was conducted for a representative urban fringe development application, with the aid of a stormwater runoff simulation model (QUALHYMO) and geographical information systems software. In developing countries like India, the use of stormwater models for modeling and sizing detention basins has yet to acquire widespread application as a standard practice. Currently, design was carried out using the rational method, which was grossly inadequate, particularly as an abundance of sophisticated software was available. Gupta et al. (1999) described the application of Australian software, ILSAX, for modeling the onsite detention basins for the Central Hospital catchment of Jaipur City, India.

Baird and Rogers (1997) reported on a case study using SWMM to determine detention volumes for a series of wet-detention ponds to mitigate increased stormwater runoff due to new urban development in Williamson, Tex.

Wetland treatment. Constructed wetlands used for stormwater treatment accumulate metals primarily in their sediment, which has the potential to produce toxic effects in benthic or aquatic organisms. A system dynamics model was developed to represent these processes and the major influences affecting pore water metal activity in a treatment wetland receiving stormwater influent. Simulation results demonstrate that chemical processes of acid volatile sulfide (AVS) and organic carbon in binding metal in reduced sediments were the greatest influences in controlling metal bioavailability (Wood et al., 1999). The wetland model utilizes a hydrology model coupled to a hydraulic stream-routing model. A depth-averaged laminar flow model was used to simulate the horizontal movement of stormwater both through and over the wetland sediments, a 400-ha first-order headwater swamp located within the Teeswater River watershed in southern Ontario, Canada. An analysis revealed that the simulated wetland streamflows were sensitive to the antecedent saturation of the wetland sediments, the storage and flow transport characteristics of the wetland sediments, and the conveyance capabilities of the wetland channel system (McKillop et al., 1999).

According to Moustafa (1999), long-term data collected at Boney Marsh, Florida and the EPA wetland database were analyzed to develop a simple tool that can be used to predict and optimize phosphorus retention in wetland treatment systems. Wetland properties such as water loading rate, water depth, P-loading rate, and water retention time were examined for their influence on phosphorus retention. The relationship between wetland properties and phosphorus removal efficiency was reduced to a simple quantitative diagram (The Phosphorus Removal Efficiency Diagram) a simple management tool that predicted expected treatment range using controllable hydrologic conditions.

A new concept, transport detention time, was proposed in this paper to describe solute-transport processes. Using this concept, a new mathematical model was developed to describe BOD₅ removal in constructed wetlands. By treating a constructed wetland as a series of continuous stir tank reactors, an n^{th} -order ordinary differential equation was derived based on the principle of mass balance and convective-dispersive equation and by introducing transfer functions and Laplace transform (Chen et al., 1999).

Traver (1999) examined the calibration and performance of a hydrologic model in recreating recorded storm events from both the stormwater wetlands and the wetlands stream, and the nutrient removal effectiveness of the stormwater wetland basin.

Nnadi et al. (1999) compared the ability of various design storm distributions to simulate the actual rainfall pattern to the runoff rates used in the design of stormwater management devices in the State of Florida using continuous simulation. A new concept, transport detention time, was proposed in this paper to describe solute-transport processes. Using this concept, a new mathematical model was developed to describe biochemical oxygen demand removal in constructed wetlands. By treating a constructed wetland as a series of continuous stir tank reactors, an n^{th} -order ordinary differential equation was derived based on the principle of mass balance and convective-dispersive equation and by introducing transfer function “Laplace transform” (Chen et al., 1999).

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Infiltration/biofiltration control practices. Munoz-Carpena et al. (1999) developed and field-tested a single event model for simulating the hydrology and sediment filtration in buffer strips. The model was developed by linking three submodels to describe the principal mechanisms found in natural buffers. They found that the performance of vegetative filter strips was governed by complex mechanisms and developed a model by linking three submodels to describe the principal mechanisms found in natural buffers: a Petrov-Galerkin finite element kinematic wave overland flow submodel, a modified Green-Ampt infiltration submodel, and the University of Kentucky sediment filtration model. A set of 27 natural runoff events (having rainfall amounts ranging from 0.003 to 0.03 m) from a North Carolina Piedmont site were used to test the hydrology component, and a subset of nine events were used to test the sediment trapping component. Good predictions were obtained with the model if shallow uniform sheet flow (no channelization) occurred within the grass filter.

Urban stormwater quality can be protected by maximizing the infiltration of frequent micro storms that account for the majority of the precipitation in urban areas. A proposed criterion was that the pre-development initial abstraction of precipitation should not be decreased by development. Heaney et al. (1999) used a linear programming model, which in turn uses information from the GIS as input data, to find the mix of functional land use types that minimizes the cost of retaining the initial abstraction at its pre-development level. To assist local governments in their efforts to develop more effective stormwater management programs, Prince George's County, Maryland Department of Environmental Resources in cooperation with the EPA developed a guidance manual for an innovative alternative comprehensive approach to stormwater management referred to as LID (Coffman et al., 1999).

Best management practices. A study of a physical model of the design of litter traps for urban storm sewers was carried out at the hydraulic laboratories at the Universities of Cape Town and Stellenbosch (Armitage and Rooseboom 2000). This study clearly showed why most designs fail and identified the use of declined screens as an approach that holds considerable promise. Low Impact Development (LID) is an innovative micro-scale runoff control strategy for WWF management issues based on the incorporation of distributed micro-scale Best Management Practices (BMP's) throughout the subcatchment (Wright et al. 2000). The potential and limitations of existing models to evaluate the effectiveness of this design approach were explored in this study. Numerical techniques for modeling overland flow from pavements were described (James and Wylie, 2000). The efficiencies of various approaches were reviewed and compared. The feasibility of a permeable pavement option in SWMM for long-term continuous modeling was explored by Kipkie and James (2000). The results indicated that it would be feasible but further testing would be needed.

A two-phase decision-making software, DELTANOE, was used for the choice of BMP in urban stormwater drainage (Barraud et al., 1999). Two phases were described: (1) an elimination phase - to exclude solutions which were identified as unworkable according to site considerations and (2) a decision phase - to compare and at least to choose a scenario with feasible solutions.

According to Murphy and Lokey (1999) a model was developed to assess urban BMP efficiency on the total pollutant load using a simple spreadsheet and Monte-Carlo style simulator. The model suggests that many BMP used to comply with the National Pollutant Discharge Elimination System (NPDES) requirements appear to have little impact on the annual load. It might be argued that many BMP need to be evaluated at the source, not the receiving stream.

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database were analyzed to develop a simple tool that can be used to predict and optimize phosphorus retention in wetland treatment systems. Wetland properties such as water loading rate, water depth, P-loading rate, and water retention time were examined for their influence on phosphorus retention. The relationship between wetland properties and phosphorus removal efficiency was reduced to a simple quantitative diagram.

A calibrated particulate transport model showed that high efficiency sweeping at weekly intervals combined with annual catchbasin cleaning provided removals approaching those of wet vaults for SS and associated pollutants, and possibly better than wet vaults for dissolved pollutants (Sutherland et al., 1998).

Real-time control.

Fuzzy logic models were used to do real time flow prediction for an urban catchment near Brussels, Belgium (Debede and Bauwens, 2000). A general method to design fast and stable mathematical models for the computation of sewer system outflow hydrographs were shown to be essential for real-time control of urban storm drainage systems (Hermann and Eberl 2000). The unknown inflow-outflow function was developed into a power series resulting in a nonlinear model. The new model formulation was tested with several urban subcatchments of a larger storm drainage network.

A real-time sensor fault detection method applicable to sewer networks was used to aid in real time control applications during wet weather (Piatyszek et al. 2000). This method consisted of comparing the sensor response with a forecast of this response provided by a model in the form of a state estimator called a Kalman filter. The Philadelphia Water Department investigated the application of real time control (RTC) to maximize the utilization of its existing combined sewer network facilities in its Southwest Drainage District (Vitasovic et al. 2000). A version of the SWMM EXTRAN routing model was compiled as a Microsoft Window Dynamic Link Library and included as part of the SewerCAT modeling environment to meet RTC requirements and exploit existing EXTRAN models of the system.

Despite considerable modeling efforts in recent years, a tool was still lacking which allows the simulation of sewer system, treatment plant and river as well as the analysis of real-time control (RTC) strategies using information from all parts of the urban wastewater system. Real-time-control (RTC) systems will be an integral part of future urban-stormwater-decision-support systems. Schutze et al. (1999) presented a software package for synchronous optimization and simulation of the urban wastewater system (SYNOPSIS) that integrated the simulation of the sewer system, treatment plant and receiving water and can be used for RTC. Marti et al. (1999) described an optimization procedure for RTC of a combined sewer system in the city of Barcelona, Spain. The control system involves measuring the variables at various points, collecting the data at the control center, processing and analyzing the data, and deciding on what actions should be taken by the actuators on the basis of the real time, self-calibrating hydraulic model. Moller et al. (1999) described a predictive urban drainage RTC system, which was based on a standard urban drainage modeling tool. The potential operational benefits associated with predictive RTC were illustrated through a test case. Reda and Beck (1999) studied the impacts of CSO on river water quality using the Multiple Continuously Stirred Tank Reactor (MCSTR) dynamic model. The potential for applying this model in a real-time context was demonstrated as a tool to support decisions regarding treatment plant operation during storm events, when it was often not possible to sustain full treatment of the incoming sewage flow.

The city of Barcelona, Spain has a 1,450 km-long combined sewer system with 10 pumping stations, 16 gates and 3 holding tanks. Marques et al. (1999) presented a remote control system that enables images obtained from a meteorological radar to predict current and future rain levels in the city of Barcelona, Spain. The received images were calibrated with the remote-controlled rain gauges in real time. Vazquez et al. (1999) examined the value of real-time management of a sewer system to reduce the impact of effluents and thus improve the quality of the host environment. The aim was to make better use of the storage capacities in the mains and tanks to reduce discharges into the environment. A multi-criteria optimization algorithm was used to provide control strategies for the components of the sewer system, e.g., sluices and pumps. Graph theory has been chosen as the mathematical tool. The study was applied to the sewer network of Saverne. Worm et al. (1999) used control strategies to equalize the hydraulic loading of a WWTP using a grey-box model of the sewer system that was based on correlation properties of flow, water level and pumping activity. The influent flow pattern showed fast transitions due to two major pumping stations in the sewer system that were operated by means of local control. By applying a stochastic flow model, calibration can be avoided since the parameters were estimated directly from the data. Hernebring et al. (1999) described the three Swedish pilot projects carried out as part of the Technology Validation Project "Integrated Wastewater" (1997-2000), supported by the European Commission.

The three Swedish projects were carried out in the cities of Helsingborg, Halmstad and Sundsvall. All three projects focus on the interaction between the sewer system and the wastewater treatment plant under variable operational conditions, created by the application of RTC in the sewer network. Pfister and Cassar (1999) described a research project that focuses on minimizing total emissions from sewer systems using RTC. The main goals of the study cover the optimum use of storage capacities, the best performance of the treatment plant, or by the dynamic management of the combined sewer system. The benefit of RTC increases if forecasted information of rainfall and runoff was taken into account. Casser and Verworn (1999) described the upgrading of the existing hydrodynamic-rainfall-runoff model HYSTEM/EXTRAN and the decision finding model INTL for real time performance, their implementation on a network of UNIX stations and the experiences from running them within an urban drainage real time control project. The main focus was not on what the models do but how they were put into action and made to run smoothly embedded in all the processes necessary in operational real time control.

A near real-time, stream-flow-simulation system utilizing continuous simulation rainfall-runoff generation with dynamic-wave routing is being developed by the U.S. Geological Survey (USGS) in cooperation with the Du Page County Department of Environmental Concerns for a 34-km reach of Salt Creek in Du Page County, Ill. (Ishii et al., 1998). The system is critical for more effective management of the Elmhurst Quarry Flood Control Facility, an offline stormwater diversion reservoir located along Salt Creek. A \$1.5 million Capital Improvement Project in the Lake City drainage basin in the northeast area of Seattle, Wash. was evaluated using XP-SWMM32. With an automatic calibration module the stormwater model showed that the system was reliable and took less time than the typical manual, trial and error approach (Ovbiebo and Kuch, 1998). Data collection and computer modeling identified deficiencies in a group of subbasins tributary to a treatment plant operated by Tulsa (Okla.) Metropolitan Utility Authority (Dillard et al., 1998). A model of Tulsa's major (≥ 250 mm) gravity lines evaluated the system's ability to pass design flow. The Greater Vancouver Sewerage and Drainage District in Can. modified the Stormwater Management Model's (SWMM) RUNOFF block to improve simulation of WWF in sanitary sewers with the addition of an effective infiltration/inflow (I/I) area factor and improvements in tracking head differences between the groundwater stage and pipe tailwater level. Calibrated results were plus or minus 15% of measurements (Kadota and Djebbar, 1998). Tsihrintzis and Hamid (1998) examined the applicability of the SWMM RUNOFF block in small subtropical urban catchments with emphasis on parameters used to calibrate the model. Balascio et al. (1998) used genetic algorithm to calibrate the RUNOFF block of SWMM. The calibrated model was used to simulate two storms with good accuracy. Los Angeles., Calif. has a wastewater collection system that serves 3.5 million people in a 1 680 km² area. The existing wastewater collection system was modeled using MOUSE (Model of Urban Sewer Systems) for dry and wet weather conditions (Price and Gonzalez, 1998). SWMM and the Corps of Engineers' unsteady flow channel network model was applied to the Big Cypress Basin Watershed in southern Fla., an area of low relief and high water table conditions, with a complex network of drainage design (Walters et al., 1998).

Petruck *et al.* (1997) developed two real-time control (RTC) strategies. The first is a pollution-based RTC and the second is a water-quality based RTC (WBRTC); these strategies seek to improve the water quality of a stream by reducing CSO volume and pollution load. The Department of Hauts de Seine which covers more than 30 urban districts on the west side of Paris, Fr. has decided to implement RTC in order to confront the problem of CSO from its CSS by using the MOUSE computer model. Preliminary studies show it would allow an 80% annual reduction of the volumes of wastewater discharged into the Seine River (Entem *et al.*, 1997). Pfister (1997) outlined the need and use of an integrated approach to combine existing model components to optimize dynamic management of CSS and WWTP.

Schilling (1996) summarized the state-of-the-practice regarding the use of RTC including applications around the world. Nelen and Broks (1996) summarized RTC use in eight Netherlands' cities. Lavallée *et al.* (1996) reported 30-60% reduction in the volume and frequency of CSOs in Quebec City, PQ, Canada using RTC. Rauch and Harremoes (1996a, 1996b) described an RTC system that includes optimization using Genetic Algorithms. Schmitt (1996a) evaluated improvements in two German combined-sewer systems from using RTC. Volume reductions were 30% in one case and 9% in the other. Sirkin (1996) cautioned that RTC should only be used after determining some necessary, preliminary information for the stormwater system. Kjaer *et al.* (1996) described using MOUSE ONLINE, an extension of the Danish Hydraulic Institutes' MOUSE model, for RTC. MacArthur *et al.* (1996) described a computer-based system for conjunctive operation of the WWTP and stormwater controls in Monroe County in upstate New York that includes the City of Rochester. Cantrell *et al.* (1996) summarized an application of HydroWorks developed specifically to use with an existing RTC system in Lima, OH, an early RTC application in the United States. Miles *et al.* (1996) described methods and models for evaluating I/I problems associated with SSO.

Optimization models.

Behera et al. (1999) present an optimization methodology for determining the design parameters (storage volume, release rate, and pond depth) of a single stormwater management pond. The methodology was extended, using a dynamic-programming procedure, to parallel catchments (each with a single detention pond). The least-cost values of pond design variables were subjected to system performance constraints, in the form of specified levels of runoff and pollution control at the outfall to a receiving water. Ndiritu and Daniell (1999) assessed the application of varying levels of optimization on model simulation performance and parameter identification using a genetic algorithm (GA) and a 10-parameter version of the MODHYDROLOG rainfall-runoff model. Four levels of optimization were obtained through the use of two GA formulations, the traditional and an improved GA, and by varying the optimization parameters with each formulation. It was proposed that the systematic verification of the adequacy of optimization should be an integral part of model calibration exercises.

Thomas et al. (1999) described the hydraulic verification of optimal control models that have been developed for large interceptor sewer systems. Both linear- and dynamic-programming models were tested using idealized interceptor sewers. The models include a simple hydraulic verification routine in which a quasi-steady approach was used to estimate interceptor sewer water profiles at each time step in the solution. Veltri and Pecora (1999) applied genetic techniques using data measured from an urban catchment to calibrate parameters from two well-known commercial modeling tools. These genetic techniques can be successfully applied to emulate a modelling environment and subsequently to calibrate indirectly the same model. Blanpain et al. (1999) described how stochastic search algorithms to be used to more fully explain the flows in a sewer network with incomplete information on its physical characteristics. The comparison, based on hydraulic simulations, showed that their method allows reduced flow and water depth deviations by at least 50%. Choi and Ball (1999) presented a decision support system for estimating optimum values of model control parameters. SWMM was used to simulate the runoff response of an urban catchment, while ARC/INFO and an optimization algorithm were employed to enhance spatial data handling and to optimise model control parameters.

Heaney et al. (1999) described a new method for optimizing the design of urban storm-sewer systems. The vertical alignment design problem was defined by a set of discrete pipe diameters and costs, excavation costs as a function of soil type, and a pre-defined horizontal arrangement of pipes and manholes for a gravity sewer. Genetic algorithms were used in place of classical techniques to arrive at the least-cost solution for a specified design storm. An example was presented to illustrate the technique. Use of mathematical models requires the estimation of model parameters. Parameter optimization was preferred to the trial and error visual comparison of observed and modelled output response, due to subjectivity and time-consuming nature of the latter approach. Dayaratne and Perera (1999) described an optimization procedure to estimate the model parameters of the urban stormwater drainage model called ILSAX. The problem of optimal water distribution to a range of retention reservoirs in an urban sewer network during rainfall events was overflows and its impact on receiving waters. A multilayer control structure consisting of an adaptation, an optimization, and a direct control layer, was proposed for the solution of this complex problem (Marinaki et al., 1999).

Pleau et al. (1998) proposed a tool to optimize long-term CSO plans which is linked to an hydraulic/hydrologic model in order to find the CSO plan that best suits the situation and reduces up to 30% of the cost of traditional approaches. A stochastic model based on physical mechanisms and formulated in continuous time to simulate water level and particulate COD at the overflow point of a Dutch combined sewer system was investigated (Grum, 1998). Preliminary results suggested that further work is needed in order to fully appreciate the method's potential and limitations in the field of urban runoff pollution modeling.

Stochastic models.

Lei et al. (1999) presented a new Stepwise Hypothesis Test Model Calibration (SHYTMC) procedure that includes explicit recognition of modeling uncertainty and system identifiability. Central in the SHYTMC procedure was the estimate of upper and lower bounds of the modeled output time series. A comparison with the result from 1,000 Monte-Carlo simulations suggests that the worst scenario approach was sufficient in the context of the SHYTMC procedure. Rauch et al. (1999) outlined the background of engineering analysis and applied the methodology to a probabilistic design problem concerning CSO reduction. The geometrical data used in stormwater models were hardly ever 100 percent correct and the process data like hydraulic roughness, overflow coefficients etc. were based upon accepted average values.

Clemens and von der Heide (1999) used Monte-Carlo simulation to evaluate the stochastic nature of this uncertain input data. The uncertainty or reliability of results produced by rainfall-runoff models was a function of uncertainties in model

parameters, input data, and model structure. Hoybye and Rosbjerg (1999) presented a stochastic instantaneous unit hydrograph model describing the catchment as a single linear reservoir with input and transfer functions treated as random processes. Errors in runoff predictions caused by errors in input data and model parameters were analyzed by solving the governing stochastic differential equation (SDE) analytically, thus quantifying - in a general way - the error propagation structure and the relative importance of input errors and parameter errors. Data from 34 rainstorms were selected to verify the analytical SDE approach. Monte-Carlo simulation, an approach developed for incorporating the uncertainty of parameters for estimating runoff in the design of polder systems in ungaged watersheds, was used to derive a set of realizations of streamflow hydrographs for a given design rainstorm using the U.S. Soil Conservation Service (SCS) unit hydrograph model (Yulianti and Lence, 1999).

The Monte-Carlo simulation approach was demonstrated in an integrated setting involving models for rainfall characteristics, CSO (CSO) loads and impacts on the surface water DO. CSO loads were modeled using event lumped non-linear regression models with rainfall as input and with overflow volume, duration and relevant event mean concentrations as output; oxygen depletion in the surface water was described using a dynamic model including oxidation of dissolved COD and nitrification. The parameters of all the models were estimated from observed data on rainfall, CSO load and surface water impacts (Grum and Aalderink, 1999). A procedure was introduced for applying the statistical approach to water table management models such as DRAINMOD, a H/WQ model used to simulate lateral and deep seepage through the soil profile. In the evaluation procedure, probability distribution functions were developed for the most sensitive input parameters, output probability distribution functions were developed using Monte-Carlo simulation, and the output probability distribution functions were used to assess the model. DRAINMOD performed successfully in the evaluative procedure in predicting the runoff, subsurface drainage volume, and the water table depth fluctuations, which were expected to be most susceptible to input uncertainty (Sabbagh and Fox, 1999).

Receiving water models.

Kellershohn and Tsanis (1999) used WASP to create a three-dimensional eutrophication model for Hamilton Harbor, Ontario, Canada. Four remedial options, namely improvements to the WWTP, the CSO, industrial discharges, and removal of WWTP, CSO, and industrial discharges were examined. Improvements in the harbor's water quality were found to range from minor in the case of CSO improvements to significant in the case of WWTP improvements. Lung and Sobeck (1999) demonstrated that modeling continues to be the most cost-effective method of water quality planning and that water resource managers should apply water quality modeling on a regular basis to support the present and future needs of the watershed. They indicated that there was a need for increased use of water quality models to review the assimilative capacity of the receiving water for regulatory control and water quality management. Petruck et al. (1999) described the water quality simulation model FGSM, developed by the German Association for Water Pollution Control (ATV) to simulate major water quality parameters of a small urban stream. The FGSM appeared to be a valuable tool for assessing not only the chronic, but also the acute effects of combined sewage overflow events.

Walker and Stedinger (1999) described the movement and fate of pathogens from wastewater and dairy sources and the resulting raw water quality for New York City, New York. Manure and *Cryptosporidium* oocysts were modeled as surface pollutants and assumed to move in response to runoff events in the six watershed-reservoir systems within the Catskill-Delaware watershed. This research highlights the importance of wastewater-derived oocysts, the need for expanded research into oocyst fate in streams and reservoirs, and the concentration of oocysts in sewage effluent. Fitzpatrick et al. (1999) presented an overview of the development and application of a time-variable nutrient based emergent macrophyte model to a southern Florida Everglades wetlands system. The model formulation included the effects of nutrient concentrations on sawgrass and cattail plant growth, nutrient uptake, and nutrient composition.

Three-dimensional simulations of estuarine circulation in the New York Harbor complex, Long Island Sound, and the New York Bight were conducted using the Estuarine, Coastal, and Ocean Model (ECOM) within the framework of a single grid system (Blumberg et al. 1999). The model forcing functions consist of (1) meteorological data; (2) water level elevation and temperature and salinity fields along the open boundary; and (3) freshwater inflows from 30 rivers, 110 wastewater treatment plants, and 268 point sources from CSO and surface runoff.

Hsu et al. (1999) described a flood and inundation forecasting model to be used for flood damage mitigation. The simulated results from the river flood model and the cell inundation model were used to calculate the flow exchanges between the river and inundation area. The results were accurate enough to be used to simulate the water stage in the river and map out the inundation area for the various design rainfalls. Huberlant et al. (1999) described the Urban Pollution Management Procedure that was developed to address the problem of protecting rivers from urban stress in a holistic and

cost effective way. The procedure allowed river systems to be modeled, with input from sewer overflows and sewage treatment works discharges, to enable assessment of minimum cost solutions. With the support of the European Commission, five pilot studies were carried out in different countries to test and demonstrate the effectiveness of this approach.

The responses of ADAPT, a daily water table management simulation model, to variations in the principal input parameters which define hydrologic response units on a watershed were evaluated (Gowda et al., 1999).

Shanahan et al. (1998) found that QUAL2E was best suited for point-source discharges and was limited when examining the contribution of NPS pollutants to river-quality degradation. The combination of models that describe the dynamic behavior of the sewer system, the WPCP and receiving water for the assessment of water pollution gives rise to a complexity far beyond what is needed (Rauch et al., 1998). Simplifications are possible because only a few types of wastewater discharge impacts typically affect the ecological state of the receiving water. Pitt (1998) described the Source Loading and Management Model (SLAMM), and gave an brief overview of its history, as well as its unique attributes and its value in determining the relationships between sources of urban runoff pollutants and runoff quality.

Watershed evaluations

A methodology was developed by the Greater Vancouver Sewerage & Drainage District to estimate future percent total impervious area using population density (Hicks et al. 2000). Percent total impervious area has been found to be an indicator of watershed health, therefore, it would be beneficial if future imperviousness could be forecast based on population growth and land use estimates. The value of benefit-cost evaluation for stormwater quality management decisions at a local level was explored using a benefit-cost analysis (BCA) screening method (Kalman et al. 2000). Ballona Creek, a major urban storm drain in Los Angeles, was used to illustrate the practicality of the benefit-cost evaluation.

The Object Watershed Link Simulation (OWLS) model was developed and used to simulate the hydrological processes within the BBWM. The OWLS model was a 3-dimensional, vector-based, visualized, physically-based, distributed watershed hydrologic model. Simulation results provided a close examination of hydrologic processes of flow separations and Variable Source Areas (Chen and Beschta, 1999). Watershed areas that generate NPS polluted runoff need to be identified prior to the design of basinwide water projects. The model TOPLATS simulates variable source area (VSA) hydrology and therefore provides an improvement to the current generation of NPS models for locating potential NPS-loading areas (Endreny and Wood, 1999). The HSPF has been calibrated for a sub-watershed of the Upper Roanoke River system. The model will provide inputs needed by other components of the study in describing environmental impacts of urbanization (Lohani et al., 1999).

Kornecki et al. (1999) evaluated the Spatially Integrated Models for Phosphorus Loading and Erosion (SIMPLE) for predicting runoff volume, sediment loss, and phosphorus loading from two watersheds. SIMPLE tended to underestimate runoff volumes during the dormant period, from November to March. Results of model evaluation indicated that SIMPLE's predictive ability was acceptable for screening applications but not for site-specific quantitative predictions. Schwartz and Naiman (1999) derived the mean and variance of planning level load estimators under mild parametric assumptions and using a distribution free approximation. Common use of the mean, median, or geometric mean of event concentrations was shown to result, in general, in biased estimates of the mean annual load. Substantive implications for regional assessments, planning, and watershed management were illustrated with a simple example drawn from Chesapeake Bay, Maryland. Alex et al. (1999) described a system of numerical models (PLASKI, SIMBA sewer and SIMBA) for simulation of wastewater production, transport and treatment, respectively. The three modules were all running under MATLAB/SIMULINK and allow integrated simulation of processes in all three-system components.

The Hydrologic Simulation Program Fortran (HSPF) has been calibrated for a sub-watershed of the Upper Roanoke River system. The model would provide inputs needed by other components of the study in describing environmental impacts of urbanization (Lohani et al., 1999). SWMM was applied to study stream-water quality due to diffuse sources on a 14.25 km² watershed in Castro Valley, Calif. The simulation was performed over a two-year period for flowrate, Cu, Pb, and SS (Khan et al., 1997).

The responses of ADAPT, a daily water-table management simulation model, to variations in the principal input parameters which define hydrologic response units on a watershed was evaluated (Gowda et al., 1999). Simulated agricultural runoff amended with sediment, nitrogen, and phosphorus, was passed through an experimental sedimentation

basin. A series of six sequential runoff events was run through the basin for each of two treatments. The treatments consisted of one-day and three-day detention times, created using a perforated riser outlet structure (Edwards et al., 1999). Most hydrologic/water quality (H/WQ) models that use rainfall as input assume spatial homogeneity of rainfall. Under this assumption this study assesses the variability induced in calibrated model parameters solely due to rainfall spatial variability. A large uncertainty in estimated model parameters can be expected if detailed variations in the input rainfall were not taken into account (Chaubey et al., 1999).

The UP (Upscaled Physically-based) hydrological modeling system to the Arkansas-Red River basin, United States was designed for macroscale simulations of land surface processes, and aims for a physical basis and, avoids the use of discharge records in the direct calibration of parameters. This was achieved in a two stage process: in the first stage parameterizations were derived from detailed modeling of selected representative small catchments and then used in a second stage in which a simple distributed model was used to simulate the dynamic behavior of the whole basin. Outputs from the model were discussed, and include river discharge at gauging stations and space-time fields of evaporation and soil moisture (Kilsby et al., 1999). The UP modeling system has been applied to the 570,000 km² Arkansas-Red River Basin (ARRB) as part of the UK NERC Terrestrial Initiative in Global Environmental Research (TIGER). The parameters of the ARRB model were physically-based, being derived either from fine-scale, sub-grid, data on the topography and physical properties of the soils, aquifers and vegetation of the basin, or from the results of fine-scale physically-based simulations. The ARRB model, as described here was a first attempt at large-scale physically-based hydrological modeling of the type outlined in the 'blueprint' for the UP system, and gives a clear, positive, indication of the nature and quality of what was currently practical with the approach (Ewen et al., 1999).

A physically-based model was used to simulate runoff in agricultural watersheds with tile drainage systems. The TOPMODEL, which was based on the detailed topographical information provided by a digital elevation model (DEM), was modified for this simulation study. The simulated hydrologic response was designed to produce several components of the outflow hydrograph which were associated with the various possible flow generation scenarios (Kim et al., 1999).

The geomorphic characteristics of an ungauged watershed were analyzed using a digital elevation model and were used to construct a runoff simulation model. A design storm was applied to the geomorphic runoff simulation model to obtain the design hydrograph (Lee, 1998). The time of concentration for a plane with urbanization from downstream to upstream could be more than four times longer than that for a plane with urbanization from upstream to downstream (Wong and Li, 1998). A physically based, distributed model, applied to a small urban watershed in Japan with an area of 66.18 ha provided a reasonable interpretation of the overall runoff and pollutant generation process in urban areas (Haiping and Yamada, 1998). Motivated by planning and rehabilitation of stormwater overflow tanks in municipal drainage systems, Haberlandt (1998) presented a simple stochastic model with spatially interpolated parameters for the synthesis of short-time increment precipitation at ungauged points. A hydrological model, based on a semi-distributed parameter, was coupled to a simple pollution transport model to analyze the alternative solutions for reduction of CSO from an urban catchment to the river Nidelva in Trondheim, Nor. (Milina, 1998). A watershed management model predicted monthly and annual water yields in two watersheds based on hydrological, geological and land use data. A subwatershed exhibited the same hydrologic behavior as the main watershed (Fuentes and Ribiero-Matos, 1998). Snowmelt Runoff Model (SRM) streamflow predictions for 1990, 1993, and 1994 seasons for the Towanda Creek basin, Pa., using a combination of elevation and land-use zones yielded more precise streamflow estimates than the use of standard elevation zones alone (Mitchell and DeWalle, 1998). The use of multiple-parameter zones was best in non rain-on-snow conditions where snowmelt was primarily driven by differences in solar radiation.

A modeling effort conducted in the Duwamish Estuary and Elliott Bay in King County, Wash. which used the 3-dimensional Environmental Fluid Dynamics Computer Code for a human and aquatic risk assessment compared potential exposure to humans, plants and animals from CSO pollutants and other sources (Schock et al., 1998). A model that described the spatial structure of hydraulic conductivity was developed using stochastic techniques and was then incorporated in the Green-Ampt and Mein-Larson infiltration models. Results showed the combined model was capable of representing the instantaneous infiltration process for spatially-variable soils under field conditions (Gupta et al., 1998). The Watershed Nutrient Transport and Transformation (NTT-Watershed) model was used to investigate the fate and transport of N in the Muddy Brook watershed in Conn. (Heng and Nikolaidis, 1998). The model captured the hydrologic and part of the N dynamics in the watershed.

Watershed Management and TMDLs

The watershed approach can be used as an integrated method for implementing Total Maximum Daily Loads (TMDLs)

(Haas et al. 2000). A discussion of how this approach could be used in Massachusetts was presented. A watershed-based assessment program identified urban stormwater discharges to small streams to be one of the most significant environmental issues in the region's long-term management plan (McCallum et al. 2000). A bacteria TMDL for the Shawsheen River in Massachusetts was described (Mockus et al. 2000). Urban stormwater was found to be the largest source of pathogens. Copper and nickel TMDLs for San Francisco Bay were integrated into the ongoing Santa Clara Basin Watershed Management Initiative with a major emphasis placed on establishing and maintaining public and industry involvement through a specially established TMDL stakeholder group (Olivieri et al. 2000). The TMDL process provided a systematic framework for dealing with long-standing water quality issues in the South Bay. The work by Jones-Lee and Lee (2000) investigated the toxicity to *Ceriodaphnia dubia* due to the contamination of runoff from residential use of organophosphate pesticides in several California cities. This paper provided guidance for the development of a TMDL for the pesticides and for controlling their impacts on the affected streams.

Controversy surrounds proposed revisions in access and recreation policy at central Massachusetts' Wachusett Reservoir, a crucial source of drinking water for metropolitan Boston (Steinberg and Clark 1999). Although tensions persist between Boston and the Wachusett region, area residents' complex valuation of the reservoir as a space of utility and a place of everyday life suggests opportunities for consensual resource coalitions and initiatives. Duram and Brown (1999) present the results of a mail survey of 64 federally funded watershed initiatives in the United States. The perceived effects of participatory watershed planning include increasing awareness of watershed conditions, heightening interagency coordination, reaching consensus on resource management plans, and lending legitimacy to final plans.

Fifty-one municipalities and county and regional agencies in the Rouge River Watershed in metropolitan Detroit, Michigan were using the "watershed approach" to solve water-quality problems from CSO, stormwater, NPS and illicit discharges (Johnson et al. 1999). Latchaw and Jarrett (1999) described a watershed restoration strategy for an urban stream in Louisville, Kentucky that was damaged by a flood. The local flood management agency, the Louisville and Jefferson County Metropolitan Sewer District, chose to change its flood and environmental management practices to reduce similar problems in the future. Letey (1999) presented the results of a case study that illustrates the interaction between the political system and science on a water management issue. Irrigation projects in the western San Joaquin Valley, California led to a situation requiring subsurface drainage and disposal of the drainage water. The original plan was to discharge the drainage water in the Suisun Bay east of the San Francisco Bay, California. Severe damage to birds associated with selenium in the water led to a reevaluation of irrigation and drainage management options.

Norton (1999) outlines the Gulf of Mexico Program (GMP) that was envisioned as a multi-stakeholder endeavor to improve coordination among Federal and Gulf State agencies and to directly involve non-government organizations in the development and implementation of actions to address key environmental problems confronting the Gulf. The GMP works to identify and implement innovative and incentive-based approaches that support Gulf State and coastal community efforts to improve the quality of life for their citizens and their environment. Sneve et al. (1999) summarize a study by the Louisville and Jefferson County Metropolitan Sewer District (Kentucky) to develop and evaluate pretreatment program performance measures that were intended to lead toward a further reduction of pollution from industrial (indirect discharge) sources. The objective of this project was to develop, implement, and assess specific performance measures designed to measure the environmental impact of the pretreatment program in a selected sewershed or watershed. The State of Washington has pioneered the use of watershed analysis as a regulatory tool since 1992 (Sturhan 1999). The rules and methods for conducting watershed analysis were developed by Timber/Fish/Wildlife, a cooperative of the timber industry, Indian tribes, environmental groups, and government agencies. Forested basins of about 10,000 to 50,000 acres were delineated across the state, and about 60 analyses have been completed, with another 35 in process.

A successful public outreach and stakeholder involvement campaign, together with a thorough engineering investigation and planning program, was helping the City of Edmonton, Alberta, Canada develop and obtain support for a cost-effective CSO control strategy (Barth et al. 1999). The Towards A Cleaner River (TACR) campaign was developed based on a need to inform and involve the public and interested stakeholders in the development of Edmonton's CSO control strategy. Schroedel et al. (1999) described efforts to finance Wisconsin's Rock River Watershed Partnership, a broad-based stakeholder group committed to addressing nutrient and other water quality management issues. Williams (1999) described the South Dade Watershed Project that analyzes the relationship between water and land use. It tries to establish consensus with stakeholders, and develops regional planning criteria that would assure a sustainable water supply and protection of species in the Everglades National park and the Biscayne Bay, while improving urban, agricultural and natural systems for south Dade County, Florida.

Australia's 'Landcare' program was a community-based participatory program established by government to tackle the problem of land degradation. Landcare involves thousands of Australians working together in locally based groups, tackling problems of common concern. Ewing (1999) reviews how the State of Victoria has responded to these challenges and suggests what challenges remain. Concerns about stormwater pollution were relatively new in Australia, and the physical and administrative systems necessary to cope with these have not fully evolved. O'Loughlin and Robinson (1999) described the growth of these concerns and how they came to be important, dealing particularly with the Australian State of New South Wales (NSW). Stormwater management practice in NSW has developed in a somewhat haphazard manner (Robinson and O'Loughlin, 1999). The evolution of current practice was critiqued. The impact of recent government initiatives including the NSW requirement to prepare catchment based stormwater plans was reviewed and suggestions made. A more rational policy framework was proposed which may have additional advantages to the current arrangements.

Eckert et al. (1999) summarize a management plan for an urbanizing river in Australia. A management system, including gross pollutant traps, automatic flocculant dosing and 16 ha of lakes was designed to address many of the failings observed in similar systems. McAlister et al. (1999) summarize major scientific studies conducted in south-east Queensland that highlight the importance of stormwater runoff as a significant contributor to the degradation of the local environment that has occurred since European settlement. These studies have identified the fine sediment component of urban stormwater as a key cause to these environmental impacts. As a consequence of these studies, a 'total catchment' approach has been developed and applied to urban stormwater quality management in Brisbane. A 1996 amendment to New Zealand's Local Government Act 1974 requires local authorities to complete asset management plans (Watts and Greenaway 1999). This required the identification and locating of all assets owned and operated by local authorities, condition and performance assessments, and the definition of accurately cost estimates of levels of service for all service delivery activities. It became clear in Christchurch that commonly accepted infrastructural asset management approaches threatened to undervalue or ignore assets with natural or social values. Currently over one hundred and sixty local government agencies in NSW, Australia have a legal requirement to prepare catchment-based stormwater management plans. Brown and Ball (1999) report on their efforts to gauge and evaluate responses by stormwater managers in the process of preparing these plans.

Clifforde et al. (1999) described developments that were currently taking place towards the creation of a comprehensive integrated management capability for urban wastewater systems. The principal vehicle by which these developments were taking place was a European Union (EU) funded collaborative project led by WRc and DHI together with numerous other partners. The project comprised both technological developments in terms of procedural issues, hardware and software and extensive practical testing via a series of pilot studies. Konig et al. (1999) described some results of an integrated model application in the Hovringen wastewater system in Trondheim, Norway. The model includes wastewater production, surface run-off, infiltration, transport and treatment under a joint Matlab/Simulink platform. The model also allows the effects of real time control to be simulated. The objective was to minimize pollution discharges to receiving waters and to define design loads for the extension of the treatment plant. Bazzurro et al. (1999) described a pilot project carried out in the framework of the EU Technology Validation Project. This pilot project was related to the combined urban drainage system of Genoa's historic center that consists of eight natural streams flowing in culverts under the urbanized area. The Venice, Italy study was one of the pilots of the "Integrated Wastewater Project under the EU sponsored Innovation Program (Pretner et al. 1999). The project aims to demonstrate that an integrated approach to the planning and management of wastewater facilities was feasible and cost-effective. The project focuses on the integrated modelling of the sewer network, wastewater treatment plant and the Venice lagoon. The model will aid in optimizing the planning and management of the wastewater structures by adopting innovative monitoring and control technologies.

Musiake et al. (1999) discussed the basic concept of improving the water cycle to better support sustainable urban systems in Japan. An investigative procedure was presented that explains how to set up the project goals and how to evaluate the water cycle. Tsunoyama et al. (1999) described efforts to restore the hydrologic cycle in the Ebi River, which flows through Funabashi City in Japan. Using a physically-based distribution model, the authors studied quantitative changes in the water circulation system over time, and deduced future changes.

Sustainability. From definitions of sustainability, Rijsberman and van de Ven (1999) derived five key elements, by which sustainable development can be described. The most important differences in the approaches can be reduced to the basic attitude towards (a) people in their environment and (b) norms and values. Combining these two components led to four basic approaches to sustainability. The suitable definition of spatial scales of investigated systems was one of the

most important questions within the water management (Stransky et al. 1999). The approach of transfer of global principles to local scale allowed determining major problems in areas investigated and establishing linkages to their causes. The urban water management objectives of ecological sustainability, economic efficiency and urban amenity required the adaptation of an integrated approach to water management. Lawrence et al. (1999) reviewed developments in the application of total water cycle based management approaches across Australia, Canada, United Kingdom and United States. The authors concluded that the need for a more integrated approach to urban water management was now being widely recognized, with a growing adoption of total-water cycle-based management, and substantial investment in ongoing studies and research related to its further application.

Loke et al. (1999) presented a framework that attempts to give an overview of the scientific tools used in urban storm drainage to water-quality problems. It tried to clarify the structure and terminology of current engineering methods by using diagrams, namely the problem identification and management scheme, the decision-making process scheme and the actual methodology overview. Recent emphasis on citizen group or stakeholder involvement in a variety of urban stormwater related policy making situations has led to the need for the technical professional to become proficient in facilitating such groups. Reese (1999) described a series of related techniques, principles and a process that have been used successfully in a variety of stormwater-related policy making settings including stormwater financing credit approaches, rate making studies, master planning and program development. Langeveld and Wiggers (1999) look at urban storm drainage and urban sanitation, not as technical problems but as conceptual ones. This paper introduces a three-stage approach, first focusing on concepts of urban water systems by combining unit-flows (water and material flows). Then the concepts were classified, and an assessment of both the possibility and desirability of the selected concepts was made. The advocated approach offers opportunities for more appropriate urban water systems by proposing new concepts for urban water systems and by guiding existing urban water systems towards sustainability.

Three municipal treatment plants and stormwater runoff were designated as sources contributing to the impairment of South San Francisco Bay, California (Tucker et al. 1999). The City of San Jose, California believed that the TMDL process served as an important way to engage stakeholders in the development of regional- environmental-management strategies. Mooney et al. (1999) presented a new TMDL-modeling framework for the Delaware River to accurately represent the current condition of the river. Novotny (1999) provided direction for TMDL research. TMDL methodologies and concepts have several problems, including determination of loading capacity only for low-flow critical periods that preclude consideration of wet-weather sources in water-quality management. Research was needed to develop watershed pollutant loading and receiving-water loading-capacity models that link wet- and dry-weather-pollution loads to the probability of exceeding water-quality standards. Chen et al. (1999) presented a decision-support system (DSS) to calculate the TMDL of various pollutants for water-quality limited sections within a river basin. The DSS includes a watershed-simulation model, a database, a consensus building module, and a TMDL module that provides a worksheet for the calculations. The methodology was demonstrated with an example application in the Catawba River, Alabama.

Borst (1998) provided an outline of the U.S. EPA research direction for modeling efforts supporting the urban watershed over the next few years. The U.S. EPA released an updated version of its BASINS modeling system (Whittemore 1998). This software integrates database queries with environmental modeling and mapping and greatly reduces the time required to manually assemble and statistically summarize monitoring data from an array of spatial databases.

Wise and Palukiewicz (1997) presented a framework for implementing watershed approaches to protect water quality. Many communities were seeking to understand how future urban development could be used as a basis for developing long-term watershed management plans (Bhaduri *et al.*, 1997). According to Pelley (1997) nearly half of the United States have adopted watershed approaches to tackle recalcitrant water-quality problems. Leland *et al.* (1997) reported that the future health of the Willamette River would depend on actions taken today. Bae *et al.* (1997) showed local environmental authorities can extend the watershed monitoring capacity through the development of a stream monitoring and stewardship program involving a partnership between community organizations. Ten watershed management projects were reviewed by the U. S. EPA (1997b) and in a separate report, successful watershed projects from State and Tribal NPS programs were also highlighted (U.S. EPA 1997c).

Kaufman and Marsh (1997) identified three classes of edge cities and assessed the impacts on stormwater runoff, groundwater contamination, and habitat fragmentation. The results indicate edge-cities may pose a significant threat of contamination to the groundwater and runoff volumes increase dramatically and water quality declines, as development displaces wetlands and creates impervious land cover. Black (1997) identified and discussed watershed functions that

dominate the hydrologic environment in order to suggest a framework for understanding and managing the growing move to “restore watersheds”. Such hydrological and ecological functions are considered in relation to the storm and annual hydrographs and to water quality. Sustainable urban drainage should maintain a good public health barrier, avoid local or distant pollution of the environment, minimize the utilization of natural resources (e.g., water, energy, materials), and be operable in the long term and adaptable to future requirements (Butler and Parkinson, 1997). An integrated approach was outlined containing both high- and low-technology solutions to appropriate problems but each case must be decided on its merits.

A public-private partnership approach to water-resources management was adopted in the San Pasqual Valley, San Diego, Calif. and included groundwater management, river-corridor management, and watershed management (Gagliardo, 1997) and control of fertilizers, pesticides, and livestock (Hon, 1997).

The strategies adopted by Singapore were to keep the flood situation under control despite the vast extent of new land developments that were continuously taking place (Check, 1997). A drainage-master plan and drainage-development programs were implemented over the years to maximize land use and the creation of aesthetic waterways to enhance the urban environment. The stormwater- and floodplan-management programs were outlined for Tulsa, Okla. and Maricopa County, Ariz. (Richman, 1997a).

Based on recent developments in urban-storm drainage, further advancement in drainage planning would require consideration of the catchment, drainage system, groundwater, treatment plant, and receiving waters as one entity and ensuring sustainable integrated development and ecological enhancement of urban streams and corridors (Ellis and Marsalek 1997). Taylor (1997) reported a case study on a stormwater-management program for the Eastern Transportation Corridor in Orange County, Calif. to mitigate freeway and highway stormwater runoff. The management program included a new concept in water-quality assessment termed evaluation monitoring that incorporated a watershed approach to determine if real water quality beneficial-use impairment in the receiving waters was occurring. Watershed planners in Wisconsin Department of Natural Resources and in county governments applied a method to estimate chemical constituents loads in non-monitored areas based on the data from a monitored stream within the watershed (Corsi *et al.*, 1997).

The community of Bellevue, Wash. resisted burdening itself with the exorbitant costs of stormwater-drainage systems. In 1974, Bellevue adopted a surface-drainage system originally out of a financial imperative and working cooperatively, stormwater engineers and parks planners wove a complex web of public open space and innovative stormwater management (Girling and Helphand, 1997). A multiobjective-mixed-integer-chance-constrained-optimization model was developed to determine design- and rehabilitation- management strategies for stormwater-drainage systems conditioned on the likelihood of exceeding the system’s conveyance capacity (Jacobs *et al.*, 1997). Model objectives included the minimization of cost and probability of system failure.

Krebs and Larsen (1997) evaluated CSO problems and a series of possible measures to enhance the system performance for the development of urban drainage towards sustainability based on case studies of mature urban-drainage systems. CSO, receiving-water quality, and decreasing groundwater levels were considered. Sewerage system and centralized aerobic WWTP should not be considered as the only possible solution for wastewater disposal. Systems with source control could avoid many problems of end-of-pipe technology by respecting different qualities of wastewater and by treating them appropriately for reuse (Otterpohl *et al.*, 1997).

The Richmond Transport Project of California, which addresses complex geologic conditions, control of surface settlement to avoid damaging adjacent residences, and an unconventional outfall design, will reduce future discharges at Baker Beach and reduce CSO into San Francisco Bay by 80% (Maiolini *et al.*, 1997).

Interest in wet-weather impacts within watersheds is at an all-time high as evidenced by the more than 300 papers presented at Watershed ‘96 (Water Environ. Fed., 1996a). St. John *et al.* (1996) described using hydrodynamic and water-quality models to evaluate the overall impact of dry- and wet-weather loads on dissolved oxygen in receiving waters near New York City, NY. Brosseau (1996) explained how the Bay Area Stormwater Management Agencies Association in the San Francisco, CA area operates. This Association has membership from seven stormwater agencies in the area. A major motivation for watershed-based approaches is improved economic efficiency. Brewer and Clements (1996) described how organizations formed a consortium to share the cost of monitoring at the watershed scale. Another source of savings from watershed management is to remove pollutants within the watershed in the most cost-effective manner. Market-based

pollutant upstream-downstream trading has emerged as a potentially valuable mechanism. Methods for discharge trading and case studies were presented by Podar *et al.* (1996); and Stephenson and Shabman (1996). Frederick *et al.* (1996) estimated the benefits of stormwater-detention systems as increased property values due to the waterfront amenity value. The results of property valuations in many areas were included. Marx *et al.* (1996) described how a watershed-based approach has resulted in more cost-effective CSO control in Boston, MA. Weiss and Lester (1996) outline how watershed ideas can be used to address SSO problems within The EPA's regulatory program. Brady (1996) summarized the accomplishments of the first five years of the EPA's watershed-protection approach. Stumpe and Hamid (1996) described how applying a watershed approach can develop more cost-effective SSO control programs. Urban stormwater is but one of many impacts in urban watersheds. Studies in Boulder, CO (Heaney *et al.*, 1996) and in Quebec City, PQ, Canada watersheds (Vescovi and Villeneuve, 1996) illustrated the complexity of urban watersheds. This complexity may be typical for urban areas because man invariably makes significant modifications to the watershed system. Roesner *et al.* (1996) described an integrated master-planning approach for management in a new development near Orlando, FL.

Stephenson (1996) compared the water budgets of an undeveloped catchment with an urbanized catchment in Johannesburg, South Africa. The results show the expected increase in direct storm runoff and the need to import water for water supply. Nelen and Brooks (1996) described the planning of a new development for about 10,000 people in Ede, Netherlands. The three underlying environmental principles are sustainability, quality, and ecology. This area has a high groundwater table so groundwater management is an important part of the project. It is planned to incorporate water conserving hardware and divert the more polluted stormwater into the sanitary sewer and consideration is being given to a dual-water-supply system. Escartin (1996) provided an overview of how Spain has used the watershed approach since 1926 to achieve more efficient water management. Grottker and Otterpohl (1996) described and integrated neighborhood urban water system for a 100 unit development in Germany which operates as a quasi-closed system.

Geographic-Information Systems (GIS)

Models and decision-support systems are incorporating GIS. The EPA recently released a package called BASINS that includes a CD for each of the EPA regions (Lahlou *et al.*, 1996). BASINS provides links to nonpoint models including HSPF and QUAL2E using ArcView. An American Water Resources Association (AWRA) conference proceedings contain several useful articles on evaluating urban-stormwater-management problems with GIS techniques (Hallam *et al.*, 1996). Shamsi and Fletcher (1996) described how ArcView can be used for a variety of GIS-related linkages to urban-stormwater models and data management including AM/FM systems. Haubner and Joeres (1996) described using GIS as a preprocessor for the Source Loading and Management Model (SLAMM) to estimate pollutant loads in urban areas including a case study of Plymouth, MN.

Automated Mapping/Facilities Management, and geographical information system (AM/FM/GIS) applications for stormwater systems were reviewed by Shamsi and Fletcher (2000). Popular AM/FM/GIS software was reviewed and six case studies were presented of applications for urban stormwater systems. Traditional hydrologic models have focused on peak discharges and NPS pollution from high-magnitude storms, but were usually of limited use in assessing the long-term impacts of land-use change (Bhaduri *et al.* 2000). A long-term hydrologic impact assessment model was developed using the curve number (CN) method linked to a GIS for convenient generation and management of model input and output. The City of Greensboro, NC has developed a Municipal Stormwater and Watershed Management Program to prioritize infrastructure maintenance, assist with stormwater permitting, track water quality data, enhance floodplain management, and facilitate stormwater management master planning (Bryant *et al.* 2000). Due to the flexibility of GIS tools and databases, the program could be expanded to include water supply system optimization, sanitary sewer system inventory and modeling, and advanced water quality modeling to support TMDL programs. A successful approach was used by the Sanitary District of Decatur, IL to develop a flexible and expandable information management platform (Kuchy *et al.* 2000). The platform was used to integrate GIS and database applications, a collection system hydraulic model, and a graphical user interface built specifically to satisfy end-user needs. A macro urban inundation model was created for Yokohama City, Japan to support benefit-cost analyses of flood control projects (Nakata *et al.* 2000). While the accuracy of the macro model (250 meter grid size) did not produce highly accurate results, the solution speed has made it an effective planning and decision-screening tool. The City of Livonia, Michigan used GIS technology to enhance the implementation of its illicit discharge elimination program (Rohrer and Beckley 2000). As a result of the GIS integration, record keeping was improved, problem areas were identified earlier, and joint efforts with surrounding communities were simplified. A site in Novi-Sad, Yugoslavia was modeled using a GIS system and the results were used to control flows through the drainage system by improving predictions of where various flow reduction techniques would work best (Makropoulos *et al.* 2000).

A GIS-based system designed to manage both sewer maintenance and I/I reduction programs was developed to integrate a wide range of over-lapping data types for these two activities (Shaffer and Greiner 2000). The system included inventory, complaints, and reporting components of the collection system. Methods for differentiating between agricultural and urban/suburban sources of water quality impairment were of interest in New England, where farms have been generally located in “mixed-use” land-use areas (Sturdevant Rees and Long 2000). This study utilized source-specific indicator monitoring techniques and a grid-based, distributed hydrologic model, incorporating them into a single GIS-based watershed management tool. A spatially variable rainfall model for a small-urbanized catchment based on records stored in a time series database was developed in Australia (Umakhanthan and Ball 2000). From the spatial patterns of rainfall, it was possible to develop individual hyetographs for each of the 42 subcatchments within this catchment. The City of Columbus used an integrated GIS/hydraulic model to address SSOs and flooding (Wolff et al. 2000). Project goals included reduction of inflow and infiltration, reduction of basement and surface flooding and improved system operations and preventative maintenance. The methods and advantages of using a GIS to plan a future sanitary sewer expansion to minimize the likelihood of SSOs was presented by Young (2000). Future flows were projected for this study based on the number of proposed new homes with existing flows being added as a known quantity.

The integration of GIS and watershed modeling was moving hydrologic and hydraulic analysis to a new dimension (Preusch and Rezakhani, 1999). BASINS--Better Assessment Science Integrating Point and Non-point Sources, a GIS-based tool developed and released by the EPA, provided a convenient interactive framework for watershed management (Parandekar and Ranjithan, 1999). Walker et al. (1999) reported the integration of the EPA SWMM runoff model and ESRI's ArcView GIS for utilization by the City of Phoenix, Arizona for decision support concerning land-use changes and pollutant loading.

The GIS Weasel, developed by the US Geological Survey, was a graphical user interface developed to aid hydrologists and other physical process modelers in the delineation, characterization, and parameterization of an area of interest, drainage nets, and modeling response units for distributed and lumped parameter models (Kenner and Love, 1999).

Fankhauser (1999) presented an automatic determination method of imperviousness from aerial photographs. The color infrared aerial photographs and orthophotos used have a ground resolution of 25 to 75 cm. A maximum likelihood classification algorithm was applied to assign each pixel to a surface category. Classification results were then overlaid with the subcatchments to determine the imperviousness of each subcatchment. Classification and overlay were carried out with the raster-based GIS IDRISI. The accuracy of the estimated imperviousness for the entire catchment areas was within 10%. Anderson (1999) described how hydraulic modeling, financial reporting and GIS have been integrated into a drainage management system in the city of Victoria in Australia. Butcher (1999) described a semi-lumped, GIS-based, transition matrix approach to estimate land use that was consistent with the level of complexity achievable in most watershed models. Several recent reservoir water supply projection studies were used to demonstrate a general framework for simulating changes in land use and resulting impacts on water quality. Butt et al. (1999) described a unified database for 14 Lake Tahoe Basin (Nevada) streams that included an inventory of riparian vegetation and stream morphology, using stream classification and riparian vegetation cover data sets. The authors provided detail on data collection and explain the development of the resultant database.

Calomino et al. (1999) described using GIS for large urban areas based on all the information needed for urban storm-water modeling. The GIS has been used together with a diffused rainfall-runoff model, MOUSE, to simulate a number of experimental events. Herath et al. (1999) presented a framework for rapid estimation of urban flood damage. The economic damage estimate was based on the property distribution within the inundated area, inundation depth and stage-damage functions. The stage-damage functions were derived from past flood data while the property distribution was represented in a detailed GIS. The method was applied to a recent flood in Chiba prefecture, Japan, and estimations and compared well with post damage assessments. Hijioka et al. (1999) described the use in Japan of distributed simulation for sewer systems to reduce inundation and water pollution events caused by CSO. An integrated system was developed to solve the problems of data-conversion from the existing sewer ledger data and the land use data. The values were generated using the detailed land use mesh database (10 x 10-m). The comparison of the simulation results with the existing rainfall data showed very good agreement. Preau and Ahmad (1999) described the components of a collection system model developed by the Sewerage and Water Board of New Orleans, Louisiana as part of a multi-year sewer system evaluation and rehabilitation program. The authors demonstrated how the utilization of a GIS in collecting and storing the data in a single location eased the model building and calibration process. Sieker et al. (1999) used GIS to process data related to the applicability of on-site, decentralized stormwater management.

Zech and Escarmelle (1999) described how distributed hydrologic models were promising but their development depends on the availability of high-resolution data able to represent urban features. Public databases from satellite imaging were not yet adequate. The authors investigated the possibility of using other kinds of databases designed more specifically for cartography. The advantages and inconveniences of such an approach were pointed out, based on two actual examples. According to Nelson et al. (1999), the Watershed Modeling System (WMS) was a comprehensive computer software application for watershed characterization and rainfall-runoff modeling in a graphical user interface environment. Through several GIS operations and tight integration with GIS databases, WMS enabled hydrologists and water resource engineers to perform rainfall-runoff modeling more efficiently than conventional modeling methods.

Difference in impervious cover estimates between land use/population density and digital vector land-based methods were as much as 55% for a single sub-sewershed (Angell et al., 1998). However, the difference in impervious cover estimates produced only minor differences in model estimates of sewershed hydrologic response. Bishop et al. (1998) evaluated maps of runoff with a 5-km and 10-km resolution from Parameter-Elevation Regressions on Independent Slopes Model (PRISM) and found less interpolation errors in the 5-km resolution. Although geographic information system (GIS) allows sophisticated visualizations for modeling NPS pollution, this should never be allowed to disguise the legitimacy or overemphasize the certainty of model results (Loague et al., 1998).

Physical parameters for a digital elevation model (DEM) generated from satellite imagery for the Cumberland Pond Dam, in Cumberland County, N.J. varied less than one percent from measured (Hourani, 1998). Using spline surfaces within a GIS, Ball and Lok (1998) produced robust and accurate estimates of rainfall and enabled real-time estimation of spatially distributed patterns. GIS enabled estimation of alternative hyetographs for different locations within the catchment. Kull and Feldman (1998) discuss the unit hydrograph method, as well as the incorporation of spatially distributed rainfall data and travel times, using radar data and GIS. The Sanitation District of Northern Kentucky developed a sophisticated implementation and response system based on GIS data to deal with wet-weather pollution (Martin et al., 1998).

Fort Worth, Tex. implemented a low budget GIS to evaluate field data and to develop recommendations for I/I and structural rehabilitation for a study area of approximately 130 km (81 mi) of the city's sanitary sewer collection system (Hegwald et al., 1998). Moeller et al. (1998) reviewed the application of a Desktop GIS to the East Baton Rouge City/Parish (La.) Sanitary Sewer Overflow Corrective Action Plan. The key functionality of the GIS was in the areas of overlay analysis and network tracing. The effects of various types of NPS pollution on the degradation of surface and groundwater within the state of Pa. was assessed (Evans and Nizeyimana, 1998). Annual loads for N and P were computed for each watershed by NPS category, including on-lot septic systems, agricultural runoff, non-agricultural fertilization, urban runoff, and atmospheric deposition. Greensboro, N.C. instituted a comprehensive stormwater infrastructure and conveyance system inventory project to be used as a citywide preventive maintenance program in addition to stormwater and urban watershed modeling applications (Bryant et al., 1998). GIS tools were applied to the estimation and prediction of stormwater flows impacting a steel plant construction site. Data layers included USGS digital and scanned image maps, SCS soils maps and engineering drawings for the site (Lieberman et al., 1998).

In an effort to quantify the many flooding problems of the Norfolk Naval Base in Norfolk, Va., the existing storm drainage network was surveyed and inventoried, hydrologic model parameters were generated using GIS, and the Extran Block of SWMM was used. Fifty projects based on this work are planned over the next 10 to 20 years and should solve 90% of the flooding problem (Small et al., 1998). The HSPF model is being integrated with ArcView to facilitate hydrologic simulation with respect to water quality, urban storm runoff and flood damage modeling for the Dardenne Creek Watershed in Mo. (Bamett and Fulcher, 1998). The Marine Corps Recruit Depot (MCRD) in Parris Island, S.C. implemented an automated mapping and facility maintenance management program designed to create physical inspection and inventory databases of the sewer infrastructure and update the sewer system AutoCAD map (automapping) (Lynn, 1998). The program consisted of a link between ArcView 3.0 which views AutoCAD map and CASS WORKS (facility maintenance management program). The city of L.A., Calif. used GIS to prepare and analyze data for water quality to facilitate the city's NPDES stormwater permit (Tam and Murillo, 1998). The system predicts water quality throughout the city and tracks identified polluters and violations.

According to Denes *et al.* (1997), an Arc/Info GIS package was used to conduct a cost-benefit evaluation study for the environmental restoration of the Passaic River adjacent to Newark, N.J. Yoon and Padmanabhan (1997) evaluated NPS pollution control for the upper Sand Hill River in eastern Minnesota by using a framework of a distributed-parameter-hydrologic model coupled with GIS and a relational-database-management system.

GIS was interfaced with a geomorphic-based-hydrologic and sediment-transport model to simulate six years of runoff and sediment data for a watershed in western Puerto Rico. The GIS/model interface is capable of modeling runoff and sediment yield over large spatial scales and is accomplished on an interactive basis in order to allow the user to have some decision-making ability (Mashriqui *et al.*, 1997). Hromadka and Yen (1997) coupled a stormwater-pollutant estimation analog to a flood-control-master plan linked to a GIS capability. The GIS functions developed land use versus area tabulations that readily input into pollutant-loading equations. A GIS based-NPS-source-simulation model was developed to simulate the hydrologic and NPS processes for the Fall Creek Watershed of New York and produced a daily-time series of estimated NPS-pollutant loadings of N and P into the Cayuga Lake (Dikshit and Loucks, 1996-1997).

An empirical-urban-stormwater runoff model, in conjunction with a GIS, was implemented in Santa Monica Bay of California in order to help identify catchments with the largest pollutant contributions. Single-family land use was responsible for contributing the highest amount of pollution with the highest concentrations in ten out of the 11 water-quality parameters tested (Wong *et al.*, 1997). Based on GIS analysis, increased preventive maintenance and rehabilitation of deteriorated sewers are two of the important elements in a program that San Diego, Calif. implemented in order to reduce SSO (Giguere *et al.*, 1997).

A decision-support and educational-software system, WATERSHEDSS (Water, Soil, and Hydro-Environmental Decision Support System) defined water-quality problems and selected appropriate control measures. The program provided management-/land-treatment decisions, assessed NPS pollution in watersheds, and used a GIS to model land-treatment effects on water quality (Osmond *et al.*, 1997). The use of the AGNPS or other ad-hoc interfaces between a distributed model and a GIS is a non-traditional method of watershed-water-quality modeling. These efficient interactive-modeling-environment systems have significantly reduced the task of watershed analysis through the use of coupled GIS databases and distributed models (Liao and Tim, 1997).

Haubner and Joeres (1997) applied a GIS to provide input parameters to the Source Loading and Management Model (SLAMM), an empirical urban-stormwater-quality model, for a small urban watershed located in Plymouth, Minn. The results demonstrated that the use of GIS in stormwater management could allow even small communities to reap the benefits of stormwater-quality modeling. Emrani (1997) addressed the integration of predictive modeling tools into a GIS which will serve as a decision-support tool to aid the development of improved maintenance plans associated with failure of storm drainage, water, and wastewater systems. Corwin *et al.* (1997) reviewed the modeling of NPS pollutants utilizing GIS as the environmental modeling tool.

Regulatory Policies and Financial Aspects

Policy

The year 2000 saw several new stormwater regulations issued nationally, and a variety of guidance documents published in support of new and existing regulations. USEPA published the final Storm Water Phase II rules in December, 1999 (Anonymous 2000b), and the members of the Sanitary Sewer Overflow (SSO) Federal Advisory Subcommittee voted unanimously to support the EPA's draft proposal for developing federal SSO regulations (Anonymous 2000a). EPA also announced plans to release a draft guidance on water quality and designated use reviews for combined sewer overflow (CSO) receiving waters in April, but not everyone was satisfied with the current guidance outline (Anonymous 2000c). Urban and agricultural wet weather sources were named as the most significant causes of impairment to our Nation's rivers and streams. However, these "impairments" were typically assessed in reference to water quality standards developed in the context of historical efforts to control dry weather wastewater sources. Therefore, the significance of wet weather impairments and the need for costly controls was debatable. Freedman (2000) explored the issue of wet weather water quality standards for CSO impacted waters, provided an overview of the obstacles to undertaking and completing the water quality standards review and revision (WQSRR) process, and included a summary of the steps that EPA and other organizations are taking to support scientifically sound and regulatory compliant WQSRRs. The amount of hydrocarbons allowed in industrial and stormwater effluents has been found to vary greatly from one locality to another or from one country to another. Some countries have mandated hardware solutions to the effluent problem, while others have stipulated a specific concentration allowable. Mohr (2000) presented the regulations governing effluents in many countries, as well as states and localities within the US and offered discussions of some of the hardware systems required by various jurisdictions. Implementation of the Total Maximum Daily Load (TMDL) provisions of Section 303(d) of the Clean Water Act has been shown to impact both point and nonpoint sources of pollution. Programs related to TMDLs often have reached beyond the purview of the agency responsible for the TMDL and have crossed into programs that operate under different regulations administered by other agencies. TMDLs thus will have significant cross-media and

cross-programmatic impacts (Staveley and Christman 2000). The Center for Environmental Research and Service (2000) at Troy State University, Alabama published a guide to developing a storm water control program to comply with Phase II requirements.

Other regulatory issues involved local stormwater managers trying to develop stormwater management efforts that meet both local needs and regulatory requirements. As currently designed, TMDL limits are based on the assumptions that there is a direct correspondence between the total mass of waste loads and ambient water quality, and that an annual cap on total wasteload allocations (WLAs) can sufficiently maintain water quality. Based on a study of the nutrient loads and water quality in the tidal freshwater Potomac River over the period 1985-1995, Sklarew (2000) suggested that hydrology was an important factor to consider in developing adequate WLAs for metropolitan tidal rivers. Furthermore, the hydrograph could be a vital tool in designing flexible and adaptive TMDLs for such areas. The City of Portage, MI has pioneered a comprehensive approach to storm water management in light of the Phase II Storm Water regulations. The city has endeavored to define "Maximum Extent Practicable" (MEP) within the constraints of available space for treatment facilities, city budget, and community support. This approach could be used by other municipalities with existing infrastructure and limited controls that now face similar storm water regulations. The approach illustrated opportunities and benefits of storm water controls implemented beyond the minimum requirement (Breidenbach et al. 2000). In November 1999, the City of High Point, North Carolina adopted a watershed protection ordinance that initiated "Phosphorus Banking" and provided greater water quality protection than the state requirements while also accommodating planned growth. Brewer et al. (2000) documented the watershed assessment and modeling approach, the successful involvement of key stakeholders, and the innovative phosphorus banking strategy.

A major effort, the Use and Standards Attainment (USA) Project, was launched by the New York City Department of Environmental Protection in August 1999 as part of its continuing efforts to maintain and improve water quality in New York Harbor and its environs. With the active participation of major stakeholders, a watershed-based approach was used to conduct an integrated evaluation of the interdependent factors affecting receiving water uses, including storm water, combined sewer overflows (CSOs), wastewater treatment, upland uses, shoreline uses, habitats, sediment and water quality (McMillin et al. 2000). The New York City Department of Environmental Protection enacted final watershed regulations prohibiting surface discharges from wastewater treatment plants, and subsequently stopped the Kent Manor housing project in the Town of Kent, Putnam County, New York. The watershed regulations included provisions for a pilot phosphorus offset program, whereby projects within the watershed with surface discharges would be approved, provided that any increase in phosphorus loading would be offset somewhere else in the watershed. van der Heijden (2000) described the steps taken to offset expected phosphorous loadings from the Kent Manor project by reducing phosphorous discharges elsewhere in the watershed. Vlier and Sandquist (2000) highlight some lessons, guidelines, and patterns emerging from the growing field of watershed-based trading. by identifying the similarities and differences in program design and linking key elements to scientific, economic, and institutional conditions in the watershed community.

The Rouge River National Wet Weather Demonstration Project in Michigan (Rouge Project) has attempted to identify the requirements of a generic comprehensive watershed management plan to meet multiple program objectives, requirements or recommendations in a wide range of individual Federal, State, and local programs to restore and protect water resources. Cave et al. (2000) identified what the Project found to be the crucial elements of a "comprehensive watershed management plan" in order to achieve multiple program objectives, such as the reissuance of NPDES permits on a watershed basis, implementation of the water quality trading programs that are currently under development, implementation of the Section 319 non-point source program, development and implementation of Watershed Restoration Action Strategies envisioned under the Clean Water Action Plan, implementation of monitoring programs and for addressing the requirements of the TMDL program. McDonald et al. (2000a) presented the preliminary findings, conclusions, and recommendations for the development of a pollutant load trading program and the modification of the existing nutrient (nitrogen and phosphorous) and TDS TMDLs and WLAs on the Truckee River, Nevada. As a result of the TMDL process, the Truckee Meadows Water Reclamation Facility had WLAs incorporated into their NPDES permit, resulting in potential restrictions on planned growth. In order to accommodate for planned growth and to meet water quality objectives, a pollutant load trading program to develop "watershed offsets" was beginning implementation. McDonald et al. (2000b) described a multiyear project to develop revised TMDLs and a pollutant-load trading program for the Truckee River.

Additional papers examined community and political issues related to WWF control programs. Lindsey et al. (2000) explore five programs led by EPA's Office of Water that address today's environmental issues in wastewater

management. Many of the programs are voluntary but regulatory programs continue to play a role in wastewater management. Through humor, Jones (2000) focused upon constraints that now inhibit a watershed solution to environmental, multi-media problems, and proposed potential remedies. The Tollgate Drainage District (Ingham County, Mich.) had to convince reluctant stakeholders that a sewer separation and stormwater outlet project had to be undertaken (and locally funded). After 2 years of education and outreach, the stakeholders not only accepted that a solution was needed, but approved a nontraditional approach (Lindemann 2000). Topping (2000) reviewed what the business community was hearing about planning and linking the planning directly to a watershed approach. Lessons from management consultants were matched to startlingly similar advice from watershed experts from federal, state and private organizations. Recommendations to focus on action and avoid “paralysis by analysis” provided a refreshing perspective for those burdened with the minutiae of the often interminable planning process (Topping 2000). It was shown that if all social and political needs of the community were not considered and addressed in a watershed protection effort, a proposed project, though technically sound and within budget, likely still would meet with significant community opposition. Halloran et al. (2000) presented one project where a front-end loaded, proactive, community oriented approach turned neighborhood opposition into enthusiasm. A new comprehensive land use plan was recently adopted to guide development of the undeveloped land area in the City of Battle Creek, Michigan. The results of this project would allow the City to gain a Certificate of Coverage under Michigan’s Voluntary General Permit for Municipal Storm Water Discharges, which has been accepted by the EPA as fulfilling the requirements of the Phase II Storm Water Regulations. As a result of performing this project, the City of Battle Creek, Michigan has learned the value of gaining stakeholder input during the watershed planning process, and has formed a Steering Committee to guide the implementation of the proposed Watershed Management Plan (Scholl et al. 2000). The decision to include the public in public works and utility projects has often been made without any ‘real’ consultation with the public or consideration of the issues that the public would be interested in. Kunz et al. (2000) discussed how the right amount and type of public involvement early in the project planning process could mean the difference between a successful project completed on time and within budget or a cancelled project after millions have been spent on design.

WWF control policy in the United States, including the ongoing implementation of EPA’s Phase II stormwater regulations, prompted a number of publications. Despite the world’s most sophisticated regulatory system, and an unprecedented level of public and private investment in wastewater infrastructure, 44% of the United State’s waterways were still unsafe for fishing and swimming, largely due to urban WWFs such as CSO and stormwater discharges. Guta (1999) discussed the challenges of identifying and managing this ubiquitous source of pollution and building sustainable cities for the future. Calamita (1999) reviewed legislation that was considered in Congress, especially the CSO Control and Partnership Act of 1999 - H.R. 828 and S. 914, and the draft Urban Wet Weather Priorities Act, both of which were intended to help create wet weather uses and standards in the United States. The paper also reviewed EPA’s efforts to comply with language added to their budget for this year that requires that they develop a guidance document to facilitate wet weather use reviews nationwide. EPA has made significant efforts to comply with this congressional mandate thereby greatly enhancing the prospects for wet weather use reviews nationwide. While the apparent direction of EPA’s Phase II stormwater regulations due to be promulgated in September 1999 appeared to encourage the use of the watershed approach, the details in the regulation do not reflect that theme.

A comparison of the directions the Phase II regulations appear to be taking and the approach of the Rouge River National Wet Weather Demonstration Project in Southeast Michigan was made and discussed by Cave et al. (1999). Murray et al. (1999) described the lessons learned in building institutional and regulatory frameworks necessary to accommodate a watershed approach to wet weather pollution management by Wayne County’s (Michigan) Rouge River National Wet Weather Demonstration Project. Also described were the consensus building strategies that were used to engage numerous stakeholders, provide them opportunities to influence decisions, and participate in the Rouge River restoration.

Hudson (1999) discussed EPA efforts to encourage the use of decentralized wastewater treatment systems by focusing on encouraging alternative technology where appropriate, promoting management systems, and coordinating its initiatives with other ongoing efforts nationwide. The EPA Long-term CSO Control Policy “Presumptive Approach” provides guidance for specific levels of control, namely, no more than four overflows on average per year or the elimination of no less than 85% of volume of the combined sewage collected in the entire system on an annual basis. The EPA believed that there was a general “equivalence” between the performance criteria that specify “percent capture” and the “number of overflows.” However, Morgan et al. (1999) demonstrated a wide variation between the storage controls developed under either of these criteria, and recommended that the municipalities should look at the site-specific nature of the CSO problem, and develop control alternatives accordingly.

A Natural Resources Defense Council report supported EPA's proposed rules to clean up stormwater runoff and storm sewer discharges in small cities and noted that the proposal's cleanup strategies have been successfully employed by more than 150 urban towns. At the same time, however, some states were complaining that the EPA proposal would undermine many state-run programs already in place (*Environmental Science & Technology*, 1999). Until now, no legal principle has been used to ensure that equity and economics were incorporated into the TMDL adoption and allocation processes. However, Clean Water Act section 305(b) may be a viable vehicle for finally including these concepts into the TMDL process (Thorne, 1999).

Stormwater discharges associated with industrial activities must be characterized for effective analysis of pollutant loads in urban watersheds. Regulatory compliance lists and inventories developed for other purposes may be poor estimators of discharging facilities. This research evaluated usefulness, flaws, and limitations of multiple forms of existing databases; then demonstrated methods to assess, combine, and correct databases to refine estimates of potentially discharging facilities in a given region (Duke et al., 1999). This research evaluated compliance with U.S. pollution prevention regulations from stormwater discharges associated with industrial activities, focusing on facilities that had failed to complete first-stage compliance requirements ("filed") approximately 5 years after the regulations took effect (Duke and Shaver, 1999). In the City of Bergen, Norway, extensive measures against point pollution sources were implemented and to be finished before the end of year 2000 for improving the receiving water conditions. Future improvements in the receiving water quality was planned through different measures aimed at reducing stormwater-meltwater runoff which causes surface pollution washoff and CSO (Thorolfsson, 1999).

Field et al. (1998) described the U.S. EPA's WWF management and pollution control research needs and anticipated research directions for the next five years, and covered areas of characterization and problem assessment; watershed management; toxic substance impacts; CSO, SSO, and stormwater runoff pollution control; and infrastructure improvement. A summary of Volume 1 of a two volume manual developed by the U.S. EPA's Office of Wastewater Management and Office of Research and Development provides a process for effective decision making and long-term planning, suggested practical guidance for municipalities to best implement their stormwater management programs, and provides a watershed protection approach (Liao et al., 1998b).

Weatherbe et al. (1998) highlighted the findings and status of implementation for WWF management of the Pollution Prevention and Control Plans funded by Environment Canada's Great Lakes 2000 Cleanup Fund and the Ontario Ministry of the Environment. American cities evolved from dense urban areas to contemporary low-density suburbs with open space. Multi-functional urban stormwater projects can be integrated into the drainage structures of cities' civic, recreational and ecological fabrics and the redevelopment of the Stapleton International Airport in Denver, Colo. is presented as an example (Wenk, 1998).

A proposed method to assess and communicate the relative public-health risk associated with coastal recreational water use in San Diego County, Calif. is based on point-source and NPS information and will be displayed geographically (Gerheart et al., 1998). Elliott (1998) determined expected rate of illness for ocean bathers near an outfall based on temporal frequency distributions of indicator bacteria concentration coupled with a concentration-response relation. Hurt (1998) presented some methodologies used to heighten public awareness for CSO related issues using Detroit (Mich.) Water & Sewerage Department's Long Term CSO Control Program policies as an example. The Surfrider Foundation started the Blue Water Task Force in 1990 and initiated a water testing program designed to evaluate human health risks from swimming and surfing in polluted water. The water testing program taught the activists that the problem with the beach-water quality was urban runoff and Surfrider activists stenciled signs on street gutters to educate people that all street gutters were connected directly to the beach (Labeledz, 1998).

After 100 years of industrial development, the Emscher area in Ger. has been presented with the need for environmental restoration and social changes (Geiger and Becker, 1998). Special attention has been paid for the choice of the future drainage system linking source control by infiltration of stormwater with collection and treatment of polluted runoff and currently a large number of pilot projects are underway which show the need for public participation to accept new technologies. Geldof (1998) reviewed urban water management in the Neth. over the last few years and provided some suggestions to cope with emissions from sewer systems, peak discharges, high ground water levels and dehydration of soil in agricultural areas and nature reserves. The solution for urban runoff and water quality management in the Birkeland basin Sandsli, Bergen, Nor. is based on urban hydrological planning and the new blue-green concept in the urban stormwater management that uses the capabilities of the basin to store runoff and melt water and to reduce pollution (Thorolfsson, 1998). The goal is to manage runoff and water quality in a way that reduces environmental damage at the

lowest possible cost. The Oakland Ravine Stormwater Treatment System project was developed as part of the NYC comprehensive program to reduce CSO discharges into receiving waters (Dinkle, et al., 1998). The project reduced discharges into Alley Creek in Queens, addressed stresses and disturbances identified within Oakland Ravine and Oakland Lake, i.e., erosion and lack of vegetation on the slopes of the ravine and deterioration of water quality, and created a natural park setting in an urbanized area. As the principal permittee of the new Los Angeles (L.A.) County Municipal Stormwater NPDES Permit, the L.A. County Department of Public Works, Calif. is undertaking one of the most comprehensive water quality monitoring programs of any municipal stormwater program in the country. The program features water quality monitoring of storm and dry weather flows from both mass emission and land-use specific drainage areas, an illegal connection elimination program, a critical source monitoring program, and a receiving-waters impact study (DePoto et al., 1998). Swamikannu (1998) reported on the process followed to reach agreement on the municipal stormwater and urban runoff program in L.A. County, Calif., the progress to date and imminent challenges that lie ahead.

Most industrial facilities in the L.A., Calif. area inadequately evaluated activities with the potential for stormwater pollution and most prepared incomplete plans for stormwater sampling and inspection procedures (Duke and Bausersachs, 1998). Only 35 to 40% of the metal plating facilities in the L.A. region recognized the need for first stage compliance to stormwater pollutant regulations. Preliminary results in evaluating compliance with stormwater regulations by industrial facilities in Calif. suggested that many facilities identified in broad-based databases do not need to comply because activities on site do not meet conditions specified in regulations (Duke and Shaver, 1998). Although industrial activities are identified as one source of pollutants in stormwater discharges from urban watersheds, the proportion of specific pollutants from industrial activities relative to other urban activities remains poorly understood. Doll et al. (1998) reviewed the key legal, financial, institutional, and political issues in setting up a stormwater facility.

A comparative study of variations in stormwater management approaches and regulations revealed additional commitment is needed to improve the water quality of the bay for several states in the Chesapeake Bay watershed (Sherman and Dee, 1998). The Mass. Water Resources Authority (MWRA) (Hornbrook et al., 1998b) developed a long-term plan for CSO control based on U.S. EPA's CSO control policy using the demonstration approach. Review of the plan by the U.S. EPA and the Mass. Department of Environmental Protection indicated that the demonstration approach was not a clear-cut process, in part due to different interpretations of the CSO control policy by the parties involved. Heath et al. (1998a) presented the process followed by MWRA to document compliance with the criteria for a successful demonstration under the U.S. EPA CSO control policy. Facilities planning for controlling CSO in the greater Boston, Mass. area in accordance with a federal court schedule were finished in July, 1997. In a study comparing four midwestern stormwater ordinances and their effects on a hypothetical subdivision, Schuller et al. (1998) found that although detention storage is required virtually everywhere in the midwest, the requirements and the resulting storage basin sizes can differ greatly. A reoriented stormwater management approach (Swietlik, 1998) should continue to address undesirable chemical changes, changes in flow rates and volumes, changes in other physical characteristics such as habitat, temperature, and DO, and maintain targeted watershed balances for nutrient cycling.

The new national water policy adopted by the S. Afr. Parliament established an integrated catchment management system for ambient water quality and point and NPS of aquatic pollution (Marjanovic and Miloradov, 1998). The repercussions of this policy and a proposed method for continuous water quality assessment are considered. D'Arcy (1998) presents a review of Scottish policies dealing with stormwater management including the formation of the Scottish and Northern Ireland Forum for Environmental Research (SNIFFER), the Scottish Environmental Protection Agency (SEPA), and some homegrown Scottish BMP to deal with poor water conditions as a result of urban runoff. Lawrence (1998) outlined the national approach to stormwater management in Aust. including implementation practices by both state and local government powers.

Lee (1997) discussed issues and regulatory requirements related to the privatization of water and wastewater services in Latin America. Lyon (1997) examined privatization law as it applies to water management in Europe and in the United States and classified it into three categories: institutional, management, and product law. In addition, Corssmit and Brunsdon (1997) discussed the transition of the Fairbanks Municipal Utilities System to private ownership, including water, wastewater, electric, steam heat, and telephone utility in and around greater Fairbanks, Alaska.

The degree of compliance in the industrial sector for General National Pollution Discharge Elimination System (NPDES) permits is not readily determined (Duke and Beswick 1997). Data for California statewide and for the Los Angeles region show about 8% — 15% of motor-vehicle transportation facilities have complied with first-stage requirements and

facility-specific evaluation in one Los Angeles County watershed suggests <50% of facilities in the industry conduct industrial activities of the kind covered by regulations; others need not comply. Luppold (1997) found considerable variation in permit cost and requirements of state and federal stormwater-discharge permits for the wood-products industry and sawmills versus chromium-copper-arsenic treating facilities. The variations in monitoring requirements appeared to be the result of different priorities and varying levels of human and financial resources and the continuous evolution of federal regulations. The renewal of the deadline for the NPDES permits was discussed. Phase I and II applications were outlined with listings of facilities covered by phase I and II permits (Christou, 1997). Ford *et al.* (1997) demonstrated and outlined the proper completion of a NPDES application..

Small CSO communities may not be required to complete each of the formal steps outlined in the National CSO Policy. Shamsi and Scally (1997) provided insight into the small community aspects of the CSO Policy as well as identified the opportunities to take advantage of the small system considerations of the Policy. Morgan and Rowe (1997) presented how the Water Works and Sanitary Sewer Board of Montgomery, Ala. reorganized to meet the uniform operational and maintenance requirements and other provisions of the U.S. EPA's draft SSO Policy/guidance document.

The U.S. EPA is working with farmers, state regulators, and environmental groups to craft a program to address NPS runoff from farming operations. These efforts are an attempt to comply with the expanded Clean Water Act's (CWA) discharge permit requirement for large pollution sources (Cooney, 1997). The U.S. EPA (1997f) published a comprehensive report on the monitoring of NPS which defined and categorized NPS, described analytical- and biological-monitoring techniques and provided data-analysis techniques, quality assurance and quality control. The total maximum daily load (TMDL) program is a water quality policy, released by the U.S. EPA, requiring state controls on NPS of water pollution (Environ. Sci. Technol., 1997a). The U.S. EPA and the Environmental Law Association have teamed up on a project which consists of the assessment of relevant state laws and incentives in order to help states combat NPS water pollution (Environ. Sci. Technol., 1997b). The U.S. EPA is funding 20 National Monitoring Program projects implemented to determine the most cost-effective BMP for preventing NPS pollution (Richman, 1997b).

Roesner and Rowney (1997) reviewed the stormwater-quality regulations of six major industrialized nations: the United States, Canada, the United Kingdom, Germany, Australia, and Japan. The differences among these countries reflected the culture of each individual country.

Reuse and Water Resources

The International Rainwater Catchment Systems Association was formed in 1989 and developed affordable rainwater catchment systems development guidelines to provide a common ground for the public and private sectors to solve water supply problems (Fok, 1998 a and b). Mitchell *et al.* (1998) described the components of urban water demand in terms of quantity and quality and discussed the opportunity for using stormwater and wastewater in Aust. Göransson (1998) proposed and reviewed stormwater projects that have aesthetic and architectural qualities for future urban environmental developments. The town of Mersing, Johor, Malaysia, identified the importance of beautification and landscaping of drains and waterways as part of the drainage and flood control plan. The landscaping of the drainage reserves and waterways will not only improve the urban drainage system and the aesthetic visual quality of the area, but will also promote the image of Mersing as a tourist destination (Chin *et al.*, 1998a).

Anderson (1996a, 1996b) described new initiatives for reusing stormwater for urban-residential- and industrial-water-supply systems in Australia. Mitchell *et al.* (1996) analyzed urban-catchment drainage by using a water-budget approach to integrate storage and reuse of stormwater and treated wastewaters for two sites in suburban Melbourne, Australia. Nelen *et al.* (1996) described the planning of a new development for about 10,000 people in Ede, Netherlands considering a dual-water-supply system. Storing the treated wastewater on-site during wet-weather periods can be more attractive than only using black water for reuse (Pruel, 1996). Herrmann and Hase (1996) described rainwater-utilization systems (RWUS) in Bavaria, Germany saving drinking water and reducing the roof runoff to the sewerage system.

Watershed Management

According to the U.S. EPA's Index of Watershed Indicators, at least 21% of watersheds have serious problems, 36% have some problems, 16% have good water quality and 28% lack sufficient information to analyze (Hun, 1998). Managers for the Joshua's Creek, a 21 km² watershed in southern Ont., Can. used a three stage process to sustain water resources in the face of rapid urban development. The process included a macro-scale watershed plan, detailed subwatershed plans, and specific stormwater management plans (Bishop, 1998). The Tualatin River Basin in northwest Oreg. experienced rapid urbanization bringing changes in land uses, increased pollutant loads to the river and its tributaries from the WPCP and

urban runoff (Jackson, 1998). Requirements defined by the Clean Water Act such as NH_3 and P load limitations were implemented in 1988 and temperature allocations were scheduled for 1997.

Municipalities are required to implement multiple regulations with regard to water resource protection including erosion and sediment control laws and stormwater requirements under NPDES. Integration of these regulation requirements under a comprehensive watershed management plan would enhance enforcement and reduce implementation costs (Pasquel et al., 1998). Coherent watershed management must rest on clear political goals regarding environmental use, risk protection and urban development (Cyr et al., 1998). The stormwater master plan must become permanently part of the water resource master plan for the whole watershed, with its objectives of flood control, erosion control and maintenance of acceptable physical-chemical and biochemical water quality, as well as assured resource use.

Sixteen state and federal agencies with management and regulatory responsibilities in the San Francisco Bay and Sacramento-San Joaquin River Estuary (Bay-Delta) in Calif. have come together in a collaborative effort with Bay-Delta stakeholders, urban and agriculture water users, fishing interests, environmental organizations, businesses and other public interests to develop a long-term solution the CALFED Bay-Delta Program (Yaeger and Ott, 1998). Integrating traditional stormwater management techniques and the watershed management approach into the city of San Francisco's existing water quality control programs reduced potential impacts of CSO and facilitated the city's efforts to comply with Phase II stormwater regulations ahead of schedule (Rourke and Brosseau, 1998). The U.S. Army Corps of Engineers, North Central Texas Council of Governments and its member local governments have cooperated in a regional initiative to more comprehensively assess the problems and opportunities of the Trinity River corridor of the Dallas/Fort Worth metroplex (Promise, 1998). The Lake County Stormwater Management Commission (SMC) of Ill. performed a multi-phase project on one residential subdivision that experienced chronic flood damages (Royal, 1998). Alternative management measures included modification of detention basins and wetlands, drainage improvement, stream maintenance, and acquisition and demolition of flood damaged residential structures. The City Center of Johor Bahru, Malaysia has been undergoing intensive urban development and redevelopment since the early 1980's and is planning for the management of urban stormwater. The factors considered in the formulation of the plan include: (1) the level of minimum acceptable flood risk; (2) town planning and other related guidelines; (3) ease of maintenance; (4) future use of the waterways; (5) accessibility to the river reserve zones; (6) flora and fauna to be used for the systems; and (7) aesthetic and safety features for recreational purposes (Chin et al., 1998b).

The Lake Pontchartrain Basin Foundation of La. developed a plan to identify water-quality and habitat problems and make recommendations. The plan addressed the impact of designated use areas by microbial contamination and suggested BMP with emphasis on disinfection and engineered microbial reduction technologies (Englande et al., 1998). The King County Water Pollution Control Division in Wash. conducted a water-quality assessment for the Duwamish River and Elliott Bay to provide information for making decisions about the future of the CSO program (Munger et al., 1998a). Wash. adopted a long-range standard for CSO control of one uncontrolled overflow per discharge point per average rainfall year. In March 1994, the city of Orlando, Fla. entered into a Joint Planning Agreement with Orange County which would facilitate the annexation of approximately 52 km² (20 mi²) of underdeveloped land southeast of the Orlando International Airport (Roesner et al., 1998). This planning effort would include the development of a Master Stormwater Management Plan (MSMP) for the annexed area using a "watershed based" approach to the management of the water quantity and quality to provide regional flood control and water maintenance of existing wetlands. Schaefer et al. (1998) described the development of a comprehensive management plan that addresses flooding, protection of environmental resources, and stormwater management regulations for a study reach within the context of existing and future development conditions throughout the watershed of Tyler Creek, Elgin, Ill.

As part of N. J.'s watershed management approach, water-resource programs, e.g., stormwater management, wastewater management, source-water protection and CSO control, will be coordinated and implemented through a statewide watershed-management process (Cohen, 1998). N. J. has maintained a federally approved coastal-zone management program for 18 years and used the Coastal Management Act to implement the State Development and Redevelopment Plan (SDRP) and the Statewide Watershed Management Plan (Frizzera 1998). The Rock River Watershed Partnership was established to conduct a full watershed study of the Wisc. portion of the Rock River as a result of stricter P restrictions imposed in 1996 (Schroedel et al., 1998). The Partnership is a cooperation of communities that line the Rock River Watershed area and efforts have been made to share information. Rudolph et al. (1998) gave an overview of the Northeast Ohio Regional Sewer District's (NORS) comprehensive watershed investigation of the Doan Brook, which serves the cities of Beachwood, Cleveland, Cleveland Heights, and University Heights and receives CSO during wet weather.

Lexington-Fayette County, Ky. began a watershed-management program that included the use of greenways, establishment of community water-quality standards, stormwater modeling, retrofitting BMP to improve stormwater quality, and stream morphology (Tapp and Uckotter, 1998). The stormwater program of the Lexington-Fayette Urban County Government used chemical monitoring techniques and biological and stream-morphological studies to quantify the current condition of the resources (Robson and Kramer, 1998). The Columbus Water Works of Columbus, Ga. developed a watershed plan to identify and quantify urban and rural wet-weather pollution sources and assess instream results of existing CSO control facilities (Turner et al., 1998). The study area of the Metro Atlanta Urban Watersheds Initiative (MAUWI) in Ga. was divided into subbasins based on factors including basin size, hydrography, land use, impervious surface and location of CSO. Each subbasin was sampled for one or more biological parameters (Hall and Richards, 1998). The MAUWI, a stakeholder driven process, produced a Watershed Improvement Guidance Document which is based on habitat, biotic integrity and water-quality data and assessments of impacts on the watersheds. The information provided communities and governmental agencies, the current state of the urban streams, pollution sources, alternatives for improvements and guidance on implementation (Richards, 1998).

A planning study for the Ile-de-France Region which includes Paris was conducted to meet dry and wet weather water quality criteria in the year 2015 (Renard et al., 1998). A watershed approach was used, and four remedial scenarios were developed including the construction of 1.4×10^6 — 1.6×10^6 Mm³ of new retention capacity and 2.5—8.5 m³/s of high-rate treatment plant capacity. Fujita (1998) presented examples of restoration of polluted or dried urban watercourses in Tokyo, Japan. Parsons Engineering Science developed the Basin Master Plan for South Creek in Sarasota County, Fla. (Cabezas, 1998) which addressed watershed-management issues. During heavy rain events, South Creek contributed to flooding and violations of levels of service in adjacent basins. A computer model summarized technical information and allowed a citizen task force to make decisions about a cost-effective management plan for development of Lake Sammanish in King County, Wash. (Richey et al., 1998).

Effluent Trading and Water-Quality Planning

Effluent trading to maintain water quality on a watershed has gained momentum recently, however the method is complex. Kerns and Stephenson (1996) addressed the key elements for a successful trading operation. The EPA (1996d) acknowledged the benefits of pollutant trading among the various sources within a watershed as a means of reducing costs, and a framework for watershed-based trading was drafted (EPA, 1996e). Imbe *et al.* (1996) did a water budget to determine the impact of urbanization on the hydrological cycle of a new development near Tokyo, Japan. A cost-effectiveness study on point sources and nonpoint sources control of phosphorus was conducted in Chatfield Basin, CO (Little and Zander, 1996). Podar *et al.* (1996) summarized progress on trading programs across the nation.

Taff and Senjem (1996) outlined four major classes of regulatory uncertainty of point-nonpoint pollutant trading systems and offered practical measures for these uncertainties.

In planning a water-quality strategy for urban areas, public relations and upfront development of partnerships were found to be critical to facilitate implementation of pollution-control plans as illustrated in the St. Catharines' case study (Toth, 1996). An ecology-based, integrated-stormwater-management approach in relation to the regulatory requirements was initiated in Germany (Schmitt, 1996b). The Rock Creek community development in Superior, CO (Galuzzi and Pflaum, 1996) used an integrated approach for the planning, design, and construction of multiuse drainage systems, including the regional-stormwater channels and detention facilities. Robbins (1996) used GIS for establishing infrastructure-inventory databases for planning and monitoring stormwater-management programs. The City of Detroit's Water and Sewerage Department developed a long-term CSO-control plan, including interconnections of drainage systems between districts and their overflow outfalls to the Detroit and Rouge Rivers (Fujita and Grazioli, 1996).

After more than a decade of research of the Water Industry's Urban Pollution Management (UPM) in the United Kingdom, its products, a UPM Manual and software tools have been widely used by major cities for evaluating their flooding- and CSO-pollution problems (Morres and Clifforde, 1996). The goals for mitigating urban-wet-weather pollution and the fundamental methodologies employed to achieve those goals were determined to be similar, according to a comparative study of urban-wet-weather-pollution-management approaches in the United States and the United Kingdom (Brashear and Drinkwater, 1996).

The Minnesota Pollution Control Agency has allowed the reduction of NPS pollution to be credited to industries' point-source discharges. Now that point- and NPS-trading standards have been established, opportunities exist for industries to

take advantage of NPS trading (Wallace and Sparks, 1997). An alternative permitting approach for the release of Pb-contaminated wastewater was discussed (Kratch, 1997a). Innovative stormwater sampling allowed a Pb-acid-battery manufacturer to obtain a new Kentucky Pollutant Discharge Elimination System permit and saved the company two-million dollars.

Schroeter (1997) discussed a methodology (and the databases used) in computing planning-level loading estimates for urban NPS from Ontario, Can. communities. Li *et al.* (1997) described the steps required to develop a preliminary stormwater-quality-management-planning strategy and presented a case study from the city of Scarborough, Ont., Can. Bolstad and Swank (1997) indicated that although most water-quality regulations, legislation, and sampling are promulgated for baseflow conditions, storm-flow conditions also warrant consideration during the promulgation process.

San Francisco, Calif. implemented a proactive water-pollution-prevention program, consisting of > 300 automotive facilities, in order to minimize wastewater- and stormwater- pollutant discharges into its CSO (Rourke *et al.*, 1997). According to Buke (1997), national “green taxes” were environmentally effective and the European Environment Agency in Copenhagen, Den. reported that these taxes were gaining acceptance. Streiner and Loomis (1997) assessed the economic benefits of urban-stream restoration and reported that property prices in areas with restored streams increased by 3% — 13%.

Permitting

Stormwater discharges associated with industrial activities must be characterized for effective analysis of pollutant loads in urban watersheds. Regulatory compliance lists and inventories developed for other purposes may be poor identifiers of discharging facilities and poor estimators of discharges. In 1996, the General Electric Plastics (GE Plastics) resin production facility located in Bay Saint Louis, Mississippi, embarked on a capital program to improve stormwater management at the facility by permitting and installing a structural BMP consisting of a *first flush* capture and treatment system for critical areas of the facility that had a potential to contribute acrylonitrile to stormwater discharges from the facility. Bennett *et al.* (1999) discussed the issues encountered during the permitting, implementation, and operation of the first flush system. A number of small cities across the United States were finding it difficult to comply with the national CSO policy issued by the EPA and have proposed alternative solutions to the CSO problem such as the site-specific designated-use reviews. In response, the EPA has begun to develop guidelines for designated-use reviews and provide technical and financial aid to several states (Mealey, 1999).

WWF control often involves unfamiliar institutional alliances, diverse groups of stakeholders, varied goals, and social or institutional resistance to new approaches. Bateman *et al.* (1999) reviewed the institutional framework the state of Florida has implemented to address stormwater problems associated with land uses. Karaitiana *et al.* (1999) discussed a partnership between the City Council of Christchurch, New Zealand and the indigenous Moari people to sustainably manage the wetlands and waterways of Christchurch. The partners have identified six generic values, including ecology, landscape, culture, heritage, recreation and drainage, which will replace only drainage as the goals of the management approach. The government of New South Wales (Australia) has initiated a stormwater management planning program to mitigate the environmental impacts of stormwater runoff from urban areas throughout the State (Sharpin *et al.* 1999). The urban stormwater management plan addresses environmental protection issues, including stormwater quality, river flow, riparian vegetation and aquatic habitat management, and was tailored to the state’s climatic, ecological, social, land use and administrative characteristics. Nielsen and Elle (1999) argued that current infrastructure hold a considerable momentum, and this momentum was a barrier to transformation to newer more sustainable technologies. The sewage sector in Denmark was an example of a technical infrastructure system whose technical, economic, and social momentum acts as a barrier to the implementation of small-scale stormwater infiltration.

Geldof (1999) discussed the impact of “qwerties” on the implementation of source-oriented approaches to stormwater management in Holland. A qwertie was an ingrained pattern that occurs in a complex process which can be eliminated only by taking measures which have sufficient critical mass and doing so at the right moment. Nine qwerties were detailed, including those of conservatism and the use of different languages. McElroy (1999) outlined efforts in the Palestinian West Bank and Gaza Strip to develop sustainable water use and reuse practices and to improve wastewater treatment so that water quality standards and regulations can be adopted that will be meaningful, measurable and enforceable. Cooperating agencies included the Palestinian Water Authority, the Palestinian Ministry for Environmental Affairs, and The United States Agency for International Development. The development of a stormwater management strategy for the City of Clarence in Tasmania illustrated a number of difficulties faced by local government agencies and communities seeking to be more environmentally and socially responsive to ecological sustainable development goals,

and the strategies available to address these difficulties. Philips et al. (1999) outlined a number of innovative approaches to the technical analysis which were used by the City of Clarence, and the principles guiding the selection of particular options. In 1994, Northern Kentucky's three counties, including 28 cities, consolidated their sewer collection systems under Sanitation District No. 1, creating the second largest public sewer utility in Kentucky, which maintained more than 1,200 miles of sanitary sewer lines. Many participating jurisdictions believe that the Sanitation District were now looking to the District to take over the operation and maintenance of Northern Kentucky's stormwater drainage systems and controls (Higdon and Eger, 1999). Because of the diverse, multi-agency and interactive nature of the watershed management approach model, both drinking and wastewater utilities often found it difficult to establish and define their role in a watershed management program. Shablen and Lauria (1999) outlined how the city of Columbus, Ohio, Division of Water and corresponding watershed stakeholders have adopted unique roles integrating federal, state and local resources to develop a source water protection partnership.

In March 1998, Portland Oregon became the first major urban area with a threatened salmonid listed under the United States' Endangered Species Act (ESA). This marked the first time the ESA has been applied in a major urban area and would result in new challenges in how best to apply and meet the Act. It would also require fundamental changes in a broad suite of activities conducted in planning, developing, and maintaining a city (Abrams and Prescott, 1999). The city of Indianapolis, Minnesota was currently fighting state permitting provisions that would make it illegal for the city's treatment facility to discharge combined sewer and stormwater flows without secondary treatment. The new regulations could cost the city \$2 billion over the next decade (*Civil Engineering*, 1999). Odeal (1999) described efforts by the Northeast Ohio Regional Sewer District to fashion a program to develop future employees and leaders for the district, which provides wastewater conveyance, CSO control, and wastewater treatment for the Greater Cleveland area (Ohio). After years of failing to meet WWTP discharge requirements, the city of Waterton, South Dakota evaluated the existing treatment process, to determine whether or not the City was truly on a path to compliance, and to assist with making any projects affordable. Schroedel and Boerger (1999) presented the success of one of the resulting recommendations, using a program manager to track all required activities to achieve compliance. Van der Heijden (1999) discussed a system of BMP intended to reduce the phosphorus loading from an area of new development and existing commercial and mixed land use. This effort was part of the New York City Department of Environmental Protection's pilot phosphorus offset program.

The Mich. Department of Environmental Quality initiated a limited Voluntary General Storm Water Permit until the U.S. EPA Phase II stormwater regulations become effective (Cowles, 1998). The Wis. Department of Natural Resources recognized that a comprehensive urban stormwater permitting program was needed for the Milwaukee River Basin as water quality in area streams and the near-shore area of Lake Michigan did not meet state standards. Aggressive voluntary efforts to control sources of rural and urban NPS pollution did not achieve desired results (D'Antuono, 1998a and 1998b). Wayne County's Rouge River National Wet Weather Demonstration Project (Rouge Project) is a comprehensive program to restore the water quality and beneficial uses of the Rouge River, a tributary to the Detroit River in southeast Mich. with significant sources of pollution from industrial and municipal point sources, stormwater runoff, and CSO (Murray, 1998). One of the Rouge Project's key findings was that major barriers to effective pollution control and water resources management are often institutional, not technical. The Rouge Project supplemented the existing regulatory program with a general permit for a sub-watershed policy in an effort to control NPS pollution (Ridgway, 1998). The NORSD service area contains approximately 20 000 ha (50 000 acres) of combined sewer area and 125 CSO for which it has an NPDES Permit (Greenland, 1998). Part of the CSO Permit requires completion of CSO control plans before 2002 and an outline was given for the plans to meet these requirements. The Community Discharge Permit Program was established as a result of grant conditions (U.S. EPA funded) for the NORSD's Heights-Hilltop and Southwest interceptors (Duke, 1998). Member communities made significant expenditures to control and alleviate SSO and the program has increased community awareness for the need for BMP to meet the performance objectives stated in the permit.

On January 9, 1998, the U.S. EPA published in the Federal Register "Proposed Regulations for Revision of the Water Pollution Control Program Addressing Storm Water Discharges" or the NPDES Storm Water Phase II proposed rule. The proposal designated two classes of facilities for automatic coverage on a nationwide basis under the NPDES program, small municipal separate storm sewer systems located in urbanized areas (about 3 500 municipalities) and construction activities (pollutants include sediment and erosion from these sites) that disturb between 0.4 and 2 ha (1 and 5 acres) of land (about 110 000 sites per year) (Kosco, 1998; EST, 1998). The U.S. EPA considered a framework for "watershed permitting" as an alternative to separate permitting of individual pollutant discharge sources which, in urban areas, would include a coordinated approach to addressing many sources in one permit or few permits, including both urban wet weather and continuous sources of pollution (Cook et al., 1998). This system of permitting helps to highlight the most

critical pollution control needs of a watershed and community and allows those needs to be addressed in the most effective and least costly manner consistent with the goals of the Clean Water Act. The Mass. Department of Environmental Protection revised the state's water quality standards to include water body classifications that reflect a range of circumstances under which combined sewers discharge and issued a new CSO Policy and Guidance Document, incorporating increased flexibility for permittees to demonstrate the combined sewer discharges were being controlled to the maximum extent feasible (Hornbrook et al., 1998a). This revision came in response to the U.S. EPA's publication of its final CSO Control Policy in April of 1994.

The EPA is adopting an interim-permitting approach for regulating stormwater discharges under its NPDES program (EPA, 1996c). The EPA developed three stormwater-discharge-permit options for industrial facilities: (1) an individual application, (2) a group application, or (3) a notice of intent for a general permit. The facility should be more cautious to select a general permit versus a multisector NPDES stormwater permit (Espey *et al.*, 1996). Stormwater discharged from iron and steel industries are regulated by the EPA Industrial Stormwater Permits Program that require the submission of a notification as soon as possible to the EPA under the Clean Water Act (Chalfant, 1996; Bralower, 1996).

Dinnison (1996) discussed the EPA's regulatory requirements for stormwater discharges and offered a practical approach to compliance with the complex federal and state stormwater regulations. A guide for obtaining a stormwater permit for construction activities at Army installations provides detailed administrative procedures for environmental staff regarding their compliance duties (Dzuray and Tang, 1996).

The California Water Resources Control Board has developed an industrial facilities database to identify the status of compliance with a facility's General Industrial Permit conditions (Duke and Chung, 1996). The Rouge River National Wet Weather Demonstration Project provided an opportunity for alternate watershed-wide NPDES permit programs to municipal stormwater discharge regulation under the Clean Water Act (Murray *et al.*, 1996).

Roth (1996) reviewed the current German law that exists for municipalities to promote alternative stormwater management, including changes in the sewage regulations and wastewater fee assessment.

Cost Analysis and Financing

New federal funding sources have become available in the US for WWF control activities. The proposed budget for the U.S. EPA in fiscal year (FY) 2001 will continue the agency's efforts to reduce funding of traditional clean water infrastructure and boost spending for projects addressing nonpoint source pollution (Calamita 2000). The Water Pollution Program Enhancements Act of 2000 (S 2417), introduced to congress in April 2000, would significantly increase federal funding for states to implement programs to address nonpoint source pollution, to assess the quality of their rivers and streams, and to collect the data needed to prepare TMDLs (Anonymous 2000d).

Several authors examined the costs of stormwater and non-point source pollution control programs. Butt and Brown (2000) report that over \$3.5 billion were spent toward nutrient controls in the Chesapeake Bay watershed between 1985 and 1996. Despite nutrient reductions, no significant improvements in dissolved oxygen levels at the bottom of the Chesapeake Bay were detected along the Bay mainstem during the warmer months, and the mouth of Bay showed marginally significant degradation during the 11-year-period. It was determined that dissolved oxygen conditions were influenced more by nitrogen than phosphorus reductions and that nutrient controls aimed at the mid-Bay region had the greatest potential for improving low dissolved oxygen conditions in the Bay's bottom waters. Fan et al. (2000a) presented a critical review of information on the costs of stormwater pollution control facilities in urban areas, including collection, control, and treatment systems. Jorgensen and Syme (2000) examined contingent valuation (CV) surveys that were used to evaluate public support for stormwater pollution abatement efforts. Their study revealed that attitude toward paying underpinned protest beliefs regarding the role of government in stormwater management and individual rights to unpolluted waterways. They cautioned that censoring protest responses in the present study would bias CV samples toward those individuals who were favorably disposed toward paying for environmental public goods and those from higher income households. Kalman et al. (2000) explored the potential value of benefit-cost evaluation for stormwater quality management decisions at a local level. A preliminary benefit-cost analysis screening method was used for a maximum extent practicable (MEP) analysis, identifying promising management practices, and identifying societal and economic tradeoffs for local stormwater problems. In the case of Ballona Creek, a major urban storm drain in Los Angeles, California, USA, benefit-cost analysis was found to be useful for evaluating and understanding stormwater management alternatives despite the uncertainties in characterizing stormwater quality and the effects of stormwater management on improving receiving water quality (Kalman et al. 2000).

The Clean Water State Revolving Fund is the United States' largest source of continuing financing for water quality projects. The 50-state managed funds are specifically authorized to, among other things, finance nonpoint source water quality projects that implement the states' nonpoint source water quality management plans that they have developed pursuant to Section 319 of the federal Clean Water Act. Steinborn (2000) described the Clean Water State Revolving Fund program and discusses potential uses of the funds for nonpoint source water quality projects. The Minnesota Legislature commissioned a six-month study to investigate the framework for a cost-benefit model to analyze water quality standards through a watershed-based approach that evaluates both point and nonpoint pollution sources (Laws of Minnesota 1998, Chapter 401, Section 59). Although watershed management has been practiced in Minnesota for decades to protect and restore water quality, this study was undertaken because of the growing understanding of the complex and often conflicting choices facing those who live in, use, and manage watersheds if watershed integrity is to be maintained over the long term (Ward 2000).

The costs for controlling sanitary sewer overflows (SSO) and combined sewer overflows (CSO) have also been examined. A problem common to many SSO equalization facilities was that the planning level cost estimates were significantly less than the final implementation costs. Keller et al. (2000) presented guidance for developing the costs of SSO equalization facilities so that their cost-effectiveness can be properly evaluated during the planning phase. New regulations governing discharge of untreated combined sewage (defined as wastewater consisting of both sanitary and storm flows during rain events) to the nation's receiving streams have challenged the traditional methods for determining cost responsibility and sewer rates for municipal wastewater utilities for the City of Detroit and Southeastern Michigan (Foster and Fujita 2000). A number of asset management tools and techniques that have been used in utilities, including wastewater utilities, were discussed by Morgan and Wagner (2000). The authors outlined a new approach for integrating these tools called Infrastructure Capital Assets Management (ICAM). The approach included modeling tools, decision support tools, and rational methodology to provide decision-makers the tools needed to develop strategies and justify retaining revenues as part of informed management of their assets (Morgan and Wagner 2000). Spartanburg Sanitary Sewer District (SSSD) in Spartanburg County, South Carolina, experienced rapid growth during the last decade, occurring primarily in rural areas. This growth created a demand for investments in all types of infrastructure. Through the use of an innovative and unique financing structure, SSSD was able to raise the required capital to finance significant sewer system improvements with minimal rate impact on existing customers, while contemporaneously improving wastewater treatment facility permit ("NPDES") compliance and reducing pollutant loading into area streams (Rich et al. 2000). In January 1998, the Milwaukee Metropolitan Sewerage District approved a ten-year Operations and Maintenance service contract with United Water Services. Tobel and Jankowski (2000) discussed the ongoing success of this award-winning project.

A survey conducted by the U.S. EPA showed that \$140 billion is needed to build, upgrade and maintain publicly owned WPCP and control stormwater and other runoff sources during the next 20 years (Christen, 1998). The mid-1999 extension of the U.S. EPA's stormwater protection scheme to 3 600 cities with populations below 100 000 will involve considerable cost. These "Phase II" cities will have to implement BMP in six different areas to receive the stormwater permits. According to the U.S. EPA, BMP implementation will cost between \$19.5 million and \$351.4 million per year, besides project start-up costs (Barlas 1998). Experiences from the city of Malmö, Swed. have shown integrated stormwater facilities are cost-effective means of achieving both quantity and quality control of urban stormwater runoff (Larsson and Kärppä, 1998). The Comprehensive Stormwater Management Plan (CSWMP) was initiated to bring various stormwater issues together so that an effective and economical policy framework and management approach could be developed for the city of Eugene, Oreg. (Andersen, 1998).

England (1998a) evaluated maintenance costs of BMP including wet ponds, dry ponds, exfiltration and infiltration trenches, porous pavement, baffle boxes, inlet weirs, grate inlet baskets, curb inlet baskets, and sediment sumps. In order for stormwater retrofit projects to successfully remove pollutants on a long-term basis, the type of maintenance needs should be considered in their design and construction. Baffle boxes were found to be effective for removal of sedimentation in small to medium size drainage basins when installed inline with existing pipe and required minimal easements and utility relocation, while grate inlet baskets and curb inlet baskets are more appropriate for small flows and drainage basins (England, 1998b). The tradeoff for these low-cost treatment methods are the perpetual maintenance expenses.

A case study of Ballona Creek in L.A., Calif. (Wilchfort-Kalman et al., 1998) showed that benefit-cost analysis helped in stormwater quality management decisions. Flexible CSO facilities that integrated the controls into the whole system have the greatest potential for cost savings from the tradeoff potential between centralized and de-centralized treatment and

between the storage and treatment level (Geiger, 1998a and 1998b). Switalski (1998) documented the Hilltop Interceptor Contract for Greater Cleveland (Ohio) from its beginning in 1991 to its completion in 1993. Six biofilters each 1 m (3 ft) deep with a treatment bed 27 m (85 ft) long and 8 m (25 ft) wide will be used to counter odor problems on the Heights-Hilltop and another interceptor with maintenance costs including periodic replacement of the substrate projected at \$0.6 million per biofilter. Up to 18,400 Singapore dollars a month could be saved in the north spine of the Republic of Singapore with the use of a dual-mode system (DMS) which uses collected roofwater for nonpotable uses. This amounts to 12.4% the current average monthly expenditure on water (Appan, 1998).

In Columbus, Ohio, (El-Hosseiny et al., 1998a) uncertainty of model results increased as model complexity decreased for small and medium storms (25—50 mm/d), however system performance was unpredictable for high hourly intensity, e.g., 100 mm/h. In determining the optimal complexity level, there was no difference between using total cost of an alternative versus design costs plus uncertainty costs. The city of Indianapolis, Indiana performed traditional sewer system evaluation surveys to eliminate I/I, costing between \$8.20 and \$9.80/m (\$2.50 and \$3.00/ft). An alternative approach addressed wet weather collection system overflows in two phases costing \$2.80 and \$1.50/m (\$0.85 and \$0.45/ft), respectively (Westropp and Bellucci, 1998). A Nashville, Tenn. study indicated that an I/I removal of approximately 14 700 m³/yr /100 m of lining may be expected from rehabilitating deteriorated sewers (Kurz et al., 1998).

The U.S. EPA (1997g) published a catalog of Federal funding sources for supporting local governments to implement watershed projects. Financial capability, along with other factors listed, may be used to negotiate reasonable compliance schedules for implementation of CSO controls (U.S. EPA, 1997h). Austin, Tex. implemented a trenchless-sewer technology, the installation of U-liners. Along with a new maintenance agreement, this will permit the city to repair approximately 35,000 ft/yr and reduce its per foot sewerline-rehabilitation cost by 44% (Water Eng. Manage., 1997a).

A general Benders'-decomposition model, which deals with solving mixed-variable problems, was developed to optimize the repair and replacement strategy for a sewer network. The model determines the least-cost solution by minimizing combined-wastewater treatment and repair associated with I/I (deMonsabert and Thorton, 1997).

Sarnia, Can. planned to upgrade its WWTP, to install four CSO-storage tanks, and to intercept stormwater runoff to upgrade, restore, and protect water quality in the St. Clair River. The first CSO tank has been installed with a cost-effective-cleaning system (Parente and Stevens, 1997). Underflow baffles were identified as a potentially cost-effective alternative for controlling CSO floatables at relatively inactive CSO outfalls by the Massachusetts Water Resources Authority. A study indicated that underflow baffles could provide up to 70% capture of floatables under a wide range of flow conditions (Walker *et al.*, 1997).

Battenfield *et al.* (1997) revealed some of the lessons learned in the development and implementation of a cost-effective solution to control the excess WWF of the Houston, Tex. sanitary system. Ahyerre *et al.* (1997) summarized three main difficulties of sewer-quality models, i.e., doubtful mathematical formulation, uncertainties on input and calibration data, and difficulties and cost of calibration. They further recommended that a clear distinction be made between management tools and research models.

Cost analysis. Onsite detention (OSD) of storm runoff decreases catchment peak flows through the routing effect of temporary storage; onsite retention (OSR) achieves the same objective by abstracting part of the urban flood wave and passing the retained water to disposal on site. Comparisons were made on the basis of site storage required (SSR) to achieve the same global peak flow reductions, environmental aspects and cost. OSR practice was shown to out-perform OSD generally in medium-large (14 ha to 210 ha) catchments with respect to SSR and, hence, cost; however, Scott et al. (1999) cautioned against use of OSR in unsuitable circumstances.

Koch et al. (1999) described an approach to the determination of flood frequency as a function of moneys that could be spent to address a road flooding problem caused by runoff from a 2-m² residential area near Washington, DC. Flood mitigation options included both culvert resizing and the provision of detention areas upstream. Challenges faced in completing this project included establishing a practical limit on the number of detention sites to be considered, and right-of-way issues in an area fully developed for single family homes.

Kreeger et al. (1999) presented a methodology for determining drainage system costs as the function of design storm recurrence interval. The Manning equation and sewer and swale cost data were combined to yield a relationship giving the cost per unit length of sewer or swale as a function of design flow. A typical residential development was created and

a stormwater modeling computer program (Rational Method and Manning equation) along with derived cost functions were repeatedly used to design and cost the drainage system for a range of recurrence intervals.

Mangarella et al. (1999) described the retrofitting of a flood control basin in Sunnyvale California and subsequent monitoring to evaluate the pollutant removal cost effectiveness of the retrofitted basin. Costs, and particularly benefits, of WWF control were often hard to quantify. Bond (1999) examined the benefits of basic infrastructure investment - water and sanitation systems, new electricity lines, roads, stormwater drainage, and other services provided at municipal level - to South African society. The direct economic benefits of infrastructure for low-income people have long been recognized, and include construction jobs, improvements in work productivity; and the growth of small enterprises. Indirect benefits include more time and resources for women; dramatic environmental benefits, public health benefits (which require infrastructure of a sufficient quality so as to enhance rather than endanger health), and the desegregation of urban society (with respect to enhanced employment, educational and cultural opportunities). McDonald and Johns (1999) use an example from Bogotá, Colombia to demonstrate how Social Benefit-Cost Accounting (SBCA) can be used to value the benefits and costs of a watershed restoration and protection project. By addressing the benefits and costs to all stakeholders, the design of watershed management programs can be improved to achieve goals in a cost-effective manner.

Rein (1999) evaluates environmental costs and benefits of implementing vegetated buffer strips (VBS) at Elkhorn Slough, Monterey Bay, California, both to the grower and to society as a whole, as a means of capturing nonmarket ecosystem values and informing decision making. The results support installing VBS as a management strategy in an erosion-prone watershed to protect water quality and preserve soil fertility, as well as to protect economic interests.

Various authors examined the costs and benefits of new or rehabilitated sewer and storm drainage systems. Backstrom et al. (1999) compared resource use in a conventional buried pipe system and a grassed swale system. Based on usage of both physical and financial resources, the grassed swale was a more economic alternative than the pipe system in areas with moderate land prices. Hasegawa et al. (1999) presented a system for assessing the need for repair and improvement of sewer pipe networks based on; 1) Decrease in flow capacity of the sewer pipe, 2) Possibility of road collapse, 3) Sewer overflow and flooding by Infiltration/Inflow (I/I), 4) Increase of treatment cost by I/I. Hirai et al. (1999) applied the Analytic Hierarchy Process procedure to prioritize portions of a drainage system reconstruction project. This system was effective because it can take into account both quantitative and non-quantitative measures of reconstruction needs. An analysis of historical development and present status of urban drainage in Switzerland and Germany conducted by Krejci and Borchardt (1999) clearly indicated that according to identified problems the current practice was associated with a high risk of misdirected investments and was not consistent with optimum system operation. The authors identified research objectives and conclude that for the near future cost efficiency should be an important issue in urban drainage. Prato (1999) presents multiple attribute decision-making (MADM) as a means of evaluating and selecting land and water resource management systems (LWRMS). Advantages of MADM were that it facilitates community-based collaborative decision making, avoids some of the ethical, theoretical and practical shortcomings of conventional economic approaches, does not require assigning monetary values to ecological services, allows consideration of multiple attributes and was not culturally biased.

McCleary (1999) discussed the costs and savings of the stormwater banking approach adopted by DeIDOT and provided useful information regarding program implementation. Doll et al. (1999) provided examples of stormwater utilities with credits for onsite stormwater management, including credits for peak runoff controls, implementation of water quality BMP, and proper maintenance of onsite stormwater facilities.

Taxes or charges for stormwater discharges were becoming a more widespread method of funding WWF control efforts. The Augusta (Maine, U.S.A.) Sanitary District was facing a projected capital expenditure of roughly \$30 million for CSO abatement alone over the next fifteen years. Recognizing that the costs for wet-weather controls could not be equitably distributed using its current system of charges, a new system was developed during 1998 and implemented in 1999 which took into account impervious areas as a means to generate appropriate levels of stormwater-based revenues (Freedman et al. 1999). Haarhoff (1999) reported on the introduction of a rainwater tax on runoff from sealed surfaces into receiving waters that was implemented by the Land (German Federal Region) of Schleswig-Holstein. The reactions of the communal authorities and their administrators responsible for the disposal of the wastewater including rainwater, and the level of success achieved by the District Water Authority in enforcing the creation of facilities for the treatment and retention of surface runoff was discussed.

The greatest obstacle to implementing a storm-drainage plan is often lack of funds to support construction and operation

of drainage facilities. Fort Bend County, TX created financial alternatives by issuing tax-exempt-revenue bonds and collecting impact fees to finance its drainage-improvement projects (Gilligan, 1996). Financing a stormwater-management program is a challenge for local governments. Collins (1996) described detailed plans for basinwide-capital-improvement plans for implementing a stormwater-management program. The establishment of an urban-stormwater-utility authority is one of the important alternatives for funding the implementation of stormwater-pollution-control systems (Benson, 1996; Reese, 1996). Roesner *et al.* (1996) described a stormwater-master plan that formulates an integrated way to finance necessary stormwater infrastructure for a new development near Orlando, FL. The EPA's Environmental Financial Advisory Board (EFAB) and Environmental Financing Information Network (EFIN) are valuable sources for creating a financing strategy for implementing Comprehensive Conservation and Management Plans (Henkin and Mayer, 1996). The EPA State Revolving Fund provides loans to local governments for financing surface-water-related infrastructure projects with 0% interest rate and could cover 100% of eligible costs (Singelis, 1996). In New Jersey, funding for CSO projects is provided through a grants- and low-interest construction-loan program jointly administered by the New Jersey Department of Environmental Protection and the New Jersey Wastewater Treatment Trust (Binder, 1996). The mechanisms used by Prince William County, VA to fund its Watershed Management Program include a county-wide-stormwater-management fee, development fees, and grants and cooperative agreements (Pasquel *et al.*, 1996).

The purpose of cost-benefit analysis of environmental projects is to assure that any development project with net environmental cost be off-set by projects with net environmental benefits. In reality, the processes are complex and their credibility is subject to question as a decision-support tool (George, 1996). A newly developed stormwater-management strategy (Mulden-Rigolen-system) that was designed to be both an ecologically and socially acceptable stormwater-drainage method was demonstrated and evaluated in the City of Zwickau, Germany (Huhn, 1996). Rudolph and Balke (1996) analyzed the cost-benefits of the new alternative stormwater-management systems for new residential developments in the cities of Dortmund and Zwickau, Germany.

Control and Treatment Technologies

Patty and Ahmed (2000) described the watershed assessment and protection plan being implemented in Peachtree City, Georgia, including both wet-weather and dry-weather sampling. These samples were to be used to ensure that standards are met and for model verification, where the model will be used to anticipate impacts from land development in the water.

Stinson *et al.* (1999) presented an overview of the EPA's Environmental Technology Verification (ETV) program which was established to overcome the numerous impediments to commercialization experienced by developers of innovative environmental technologies. The purpose of ETV was to provide such data and information to the customer groups that require them in order to accelerate the real world implementation of improved technology. This publication described the ETV approach and two recently initiated pilot programs for verification testing of WWF and source-water protection technologies.

A case study was reviewed which applied urban design planning for a commercial redevelopment project in the City of Vista, California involving the replacement of a 1950 concrete flood control channel into a restored natural "river walk" linear park. The proposed creek restoration would provide the focal point for an economic revitalization of the downtown area that includes restaurants, shops, and entertainment center, with the creek providing the common linkage (Phillips, 1999). Wong *et al.* (1999) discussed the various issues and performance considerations associated with the comparisons of ponds and wetlands for stormwater pollution control. Ponds and wetlands were commonly used in urban design to meet a number of urban planning objectives including the management of urban stormwater for water quality improvement.

Brashear *et al.* (1999) described a project to deliver stormwater management information through the World Wide Web. The Texas Nonpoint SourceBOOK was a Web-based stormwater quality guidance document for public works professionals in the State of Texas. The SourceBOOK allowed users to access a wide variety of stormwater management information including the applicability and cost-effectiveness of stormwater management practices, legal authority issues, funding mechanisms for stormwater programs and local water-quality information. Most importantly, a database of over 100 BMP was available for users to access, allowing a diverse audience to become familiar with BMP principles and application procedures (sizing, design principles, etc.).

The site planning and design phase of land development projects presented the best opportunities for, and was critical to,

reducing the impacts of development on the quality of the nation's waters. Recognizing the need for guidance in site planning and design, the San Francisco Bay (California) Area Stormwater Management Agencies Association (BASMAA) published the document "Start at the Source - Residential Site Planning and Design Guidance Manual for Stormwater Quality Protection" and a second edition in 1999 that also included guidance for industrial and commercial development. The manual communicated basic stormwater management concepts and illustrates simple, practical techniques to preserve the natural hydrologic cycle (Richman and Bicknell, 1999).

Drainage Design and Hydraulics

An exponential relationship exists for underflow baffles between the vertical velocity and the turbulent component of the horizontal velocity. Dimensioning analysis indicated that long chambers with intensive designs would be required for an 80% floatables removal efficiency (Cigana et al., 1998a, 1998b and 1998c).

A nine year, \$186 million rehabilitation program in Dallas, Tex. used trenchless technology for the smallest pipes and 3 m (120 in.) diameter diversion pipes with the ability to throttle flow (Almeida, 1998). During wet-weather events the city now has the ability to fill pipelines in the wastewater collection system without creating overflows. The Rouge Project used several methods to identify illicit connections. Data suggested there were 5 260 illicit discharges and 3 600 failing on-site sewage systems in the watershed (Johnson and Tuomari, 1998). Evanston, Ill. conducted a large-scale project to reduce the frequency of backups of combined sewers into residents' basements. An inlet control project increased the protection against basement backup to 50 to 100 year recurrence levels while significantly lowering cost (50%) over traditional solutions (Figurelli et al., 1998). A study conducted in the city of Salem, Oreg. revealed modification of interior plumbing of homes and installation of backwater valves, and the modification of the interior plumbing of the homes and installation of new service and ejector pumps the most effective solution to flooding of residential basements with raw sewage during storm events (Roley, et al., 1998).

In Houston, Tex. a 15% reduction in the peak rainfall-dependent I/I was factored into the design of all overflow control projects as a credit for I/I estimated to be eliminated by structural rehabilitation. Because of the inherent variability of I/I, response in sewer systems flow reductions due to rehabilitation generally cannot be definitively quantified and at best, a range in reduction can be established (Samson et al., 1998). A slipline pipe was installed on the NORSD Westerly Interceptor project (Dell' Andrea, 1998) to relieve I/I and exfiltration at a cost significantly less than a total replacement would have been. A slightly smaller diameter pipe section is inserted inside the existing sewer and the annular space between the two is filled with grout. Montgomery, Ala. monitored the rehabilitation of manholes in a sanitary sewer system and found that a cementitious mortar, in places covered with a coal-tar epoxy liner effectively sealed out I/I from the system (Holmberg and Rowe 1998). Their experience also indicated that proper surface preparation is vital to ensure adhesion between the mortar and substrate for lasting benefits of the work. The NORSD assessed the condition of the interceptors and CSO (Duke and Knott, 1998). Guidelines for manhole and pipeline defect classification were established and procedures for condition assessment were also developed. Anderson and Curtis (1998) discussed how a hydraulic model can be developed that will ensure the level of accuracy that should be required as part of any hydraulic evaluation of wastewater piping systems involving technologies such as the Global Positioning System (GPS).

Because SSO and CSO pumped-relief force mains are normally emptied after use to prevent odors and deposition, the volume of air to be vented with each start up may exceed the capacity of typical air relief valves. Typical air relief designs include venting of full force mains where small amounts of entrained air are vented from the pipe while operating at the design working pressure (Cavalieri and Devlin, 1998). Hydraulic modeling indicated that a 1 m (42 in.) relief siphon with a 170 000 m³/d (45 MGD) capacity for Braintree and Weymouth, Mass. should result in a 78% reduction in overflow volume per year, with number of overflows reduced from 38 to 15 (Spearin et al., 1998). Flowmeters installed in the siphon at the Green Bay (Wis.) Metropolitan Sewerage District's Fox River Crossing and at three locations along the upstream interceptor sewer provided data used to develop projected peak flows to be expected during design storms ranging from 5 to 50 year frequencies. The evaluation showed that the siphon's existing capacity was inadequate to handle the projected peak flow from even a five-year storm (McCarthy and Blauvelt, 1998). Although traditional studies interpreted Bellmans Creek near Jersey City, N.J., to be dominated by tides, Sela (1998) found that fluvial flooding from storm runoff was dominant on most of its length and that the corresponding design flood level exceeded estimates of previous studies by approximately 1 m (4 ft).

Several days of heavy precipitation induced flows which exceeded the capacity of pipes and basins at a site in Wash., causing a road failure, and 227 000 m³ of wastewater were discharged to Puget Sound. Emergency measures were undertaken to repair the damage within three weeks of the failure (Langer et al., 1998). An underground utility in

Lynchburgh, Va. was restored to full capacity after a blockage was removed. Before the cleaning, any rain longer than ten minutes would cause raw sewage to bypass into the Blackwater Creek and James River (Water Engineering and Management, 1998). Stop-ups or backups caused by trash or grease accumulations have a significant probability of being caused by backwater effects in the collection system, rather than by illegal discharges (Conegliano, 1998). Gow (1998) reviewed the NORSD wastewater collection system which includes 334 km (207 mi) of intercepting sewers within the boundaries of Cuyahoga County, Ohio.

Faced with declining water quality as a result of uncontrolled inflow of poor quality runoff from within the watershed, managers of Sweetwater Reservoir opted to construct the Sweetwater Urban Runoff Diversion System (URDS), a diversion system to intercept and divert poor quality runoff upstream of the reservoir and convey it downstream of the reservoir (Bottcher et al., 1998).

Roesner (1998) discussed the impact urbanization has on water runoff intensities and effects to the receiving waters. A guidance manual for WWF drainage systems in newly urbanized areas is being developed and will examine the history of WWF management and present some recommended strategies for newly developing areas (Pitt et al., 1998a). A related study (Heaney et al., 1998a and 1998b) presented some highlights of the initial phases of innovative urban stormwater managements systems for the 21st century with results of an extensive literature review and preliminary evaluations of alternative future scenarios. The development of a combined sewer network for new urbanized areas, associated with inline retention and RTC was cheaper than separate sewers (despite provincial regulation providing new urban developments have separate sanitary and storm sewers) and reduced the impact of stormwater to the environment for Montreal, Can. (Charron et al., 1998).

The drainage system of Port St. Lucie, Fla. is made up of roadside swales, a series of drainage right-of-ways, and canals and waterways that eventually lead into the north fork of the St. Lucie River. To address swale drainage problems, the city purchased various types of all-terrain excavators including three 'Swamp-Meisters' which have large, powerful mulching/cutting heads (Thacker and Gonzales, 1998).

Grace (1997) described four case studies of marine-outfall rehabilitation and maintenance where obstructions had caused serious problems in wet-weather- and wastewater-effluent drainage. Larsen *et al.* (1997b) reported that after construction costs of 6.8 million dollars for regional-sewer rehabilitation in the Broward County, Fla. Southern Regional Wastewater Collection System, I/I is still a problem. The repair project eliminated 5.64 million gallons per day (mgd) of extraneous flow but an estimated 10.5 mgd still enters the system. An evaluation of eight basins in Seoul, Korea revealed that every five meters the sewer systems needed repair and this was made worse by I/I, resulting in poor operation of the WWTP. Trenchless-rehabilitation technology was recommended as a solution (Parks, 1997). Guajardo and Gogers (1997) developed a roadway drainage plan with improvements on existing discharge flows to the receiving stream in the Houston, Tex. Pazwash and Boswell (1997) presented specific methods to collect and use roof runoff for lawn and landscape watering, car washing, and deck and driveway cleaning.

Bhaskar *et al.* (1997) used a physically-based-rainfall-runoff-estimation method. The geomorphological-instantaneous-unit hydrograph (GIUH) estimated flooding from wet weather and obtained results comparable to observed events. Bonta (1997) derived frequency distributions as an alternative method for determining watershed curve numbers from measured data, treating rainfall and flowrate data as separate frequency distributions.

Over 7,900 ft of 24 in. — 54 in. diameter failing sewer pipe was repaired using sliplining and cured-in-place-lining techniques in Baton Rouge, La. (Water Eng. Manage., 1997b). Ahmed *et al.* (1997) evaluated the performance of subdrainage systems for the mitigation of WWF and found performance to be dependant on pavement and drain types. Young (1997) presented a methodology for the identification, assessment, and novel solution of the stormwater-overflow-pollution problem in a typical small urban catchment.

The U.S. Department of Transportation, Federal Highway Administration (U.S. DOT) (1996a and 1996b) published a two-volume report on the evaluation and design of highway- stormwater-runoff-control facilities.

Burrows *et al.* (1997) reported on the development of a low-cost system based on monitoring the behavior of flap valves on numerous major outfalls along the Thames River in the United Kingdom. The modeling approach was based on the principle of conservation of angular momentum and its application to experimental data for circular gates. The recommended calibration offered ± 20 — 30% flow prediction accuracies for gate openings angles $> 20^\circ$.

Djebbar and Wisner (1997) compared three unit hydrographs based on the ability of each to reproduce observed stormwater runoff in urban watersheds that had different hydroclimatic conditions. The study addressed the frequently reported problem of time-step selection in hydrological modeling. Pruski *et al.* (1997) developed a procedure to determine the maximum-surface-runoff (MSR) volume by employing a constant infiltration rate after prolonged wetting of the soil. This procedure is applicable where the rainfall intensity/duration/frequency relationship is known.

Holmberg (1997) addressed the techniques for proper project execution and quality control when applying cementitious coatings (in a sewer environment) performed in a sewer-basin-manhole-rehabilitation project in order to meet three goals: the elimination of I/I, limited structural rehabilitation, and general corrosion protection. Rajaratnam *et al.* (1997) performed physical-model studies on the hydraulics of stormwater-dropshafts. The energy loss in the dropshaft was about 80% — 95% of the total hydraulic loss.

O'Loughlin *et al.* (1996) presented examples of design problems and research and development work on small stormwater drainage systems, relating these to scale effects in space and time. There is a potential for extending the lower boundaries of current design methods through detailed studies of small drainage systems. Blaszczyk and Ashley (1996) presented new approaches for the design and operation of combined sewers to control sediment problems. Results from a field study conducted in Poland and how application of these criteria aids in the development of self-cleansing velocities for full and partially-full flows were discussed.

Stormwater Best Management Practices (BMP)

A variety of projects employed stormwater control as part of a larger environmental restoration effort. Aichinger (2000) reported on a stormwater BMP program that included the construction of three stormwater treatment basins, implementation of a watershed education program, and completion of an alum injection system for removal of phosphorus from stormwater. The application of alum treatment had several unique features: its design to address treatment of base stream flows, storm event flows, and seasonal changes in stormwater temperature and pH; its off-line system design; its thorough bench-testing to address dosing for optimal phosphorus removal under various conditions; and its design to comply with specific dissolved and total aluminum discharge standards. Mecklenburg County North Carolina's Department of Environmental Protection (MCDEP), has undertaken a comprehensive restoration in the Edwards Branch watershed. The basin-wide BMP plan included design and construction/implementation of wet ponds, multiple pond/marsh systems, sand filters, bioretention areas, riparian forest buffers, level spreaders, filter strips, stream bank stabilization, stream channel restoration, constructed wetlands, and targeted public education programs. The physical structures had to be designed as retrofits of existing facilities in the developed watershed or integrated into the existing land uses. Baseline, construction, and post construction monitoring, using EPA stream habitat assessment protocols, ambient water quality monitoring, fish and benthic macroinvertebrate surveys, and channel cross section monitoring, have been and continue to be used to collect data to justify implementation of successful practices (Baker *et al.* 2000). In Portage, Michigan, a storm water treatment system currently under design will significantly increase the quality of life for city residents while meeting and exceeding regulatory requirements. This new regional facility is to be linked to a recreational trail way system, provide treatment for runoff from 1.9 km² (463 acres) within the highly developed urban core targeting 80% pollutant removal rates, and double the length of existing trail ways in the city (Jacobson *et al.* 2000). Mattson *et al.* (2000) presented a study of urban stormwater impacts in the Severn Sound Area of Ontario, Canada. The study objectives were (1) characterization of dry weather and runoff quantity and quality; (2) monitoring effects of stormwater runoff on the bacterial concentrations at an urban bathing area; and (3) development of pollution control plans for the participating urban municipalities in the Severn Sound watershed with an overall goal of a 20% reduction of stormwater phosphorus loads.

The City of Rockledge, Florida developed and implemented a Stormwater Management Program using a watershed-wide management approach, which included stormwater facility inventory maps along with necessary hydrologic, hydraulic, and water quality data (Schmidt *et al.* 2000a). The Stormwater Master Plan for Miami International Airport (Florida) included comprehensive evaluations of hydrology, hydraulics, water quality, BMPs, and facility planning in phases to allow cost-effective implementation of the plan while aircraft operations continued and increased. A variety of constraints were identified, including the protection of aircraft passenger safety (no fog or bird attractants) and the environment (water quality, manatees, and hazardous material cleanups) (Schmidt *et al.* 2000b). Lake Macatawa, near Holland, Michigan, was listed by the Michigan Department of Environmental Quality's 303(d) nonattainment list; high phosphorus concentrations from nonpoint sources and excessive turbidity were found to be the main contributors to poor water quality. A list of 44 BMPs were considered as controls for reduction of the nonpoint phosphorus load. An objective and

quantitative procedure, based on economic production theory and marginal cost analysis, was developed to assign the proposed level of effort and subarea watershed locations for each BMP (Scholl 2000). In order to comply with the County's MS4 Stormwater NPDES permit, the Anne Arundel County (Maryland) Department of Public Works (DPW) had to field locate all storm drain outfalls and stormwater management ponds, assess their structural condition, perform a general assessment of stability of downstream channel conditions, and identify stormwater management retrofit opportunities for implementation as County capital improvement projects. A relational database has been developed for data management and analysis, with a direct link to GIS coverages (Smith et al. 2000b). Templeton (2000) presented an overview of the Nutrient Management Strategy for point source dischargers to North Carolina's Neuse River and the State's experience in implementing the Strategy thus far. Whitman et al (2000) described two efforts to test new stormwater retention technologies in the Los Angeles, California watershed. These efforts were designed to better manage stormwater and to address the impacts of urbanization and imperviousness. The efforts included reducing impervious cover and planting trees at public schools. The state of Florida was developing urban BMPs to control urban runoff impacts on the Everglades (McPherson et al. 2000).

Treated stormwater has been suggested as a candidate for irrigation water or similar reuses. Heggen (2000) reviews the challenges of rainwater catchment in sustainable development. Fan et al. (2000a) discussed current urban stormwater control and treatment technologies, and the feasibility of reclaiming urban stormwater for various purposes, including a hypothetical-case study illustrating the cost-effectiveness of reclaiming urban stormwater for complete industrial supply. In connection with efforts to restore water quality in Santa Monica Bay, The City of Santa Monica, California has diverted its major dry-weather stormwater flows from the Pico-Kenter and Pier Storm Drains to the City of Los Angeles' Hyperion Wastewater Treatment Plant located a few miles to the south. Recently the city concluded that the dry-weather flows could be treated and economically reused in place of potable irrigation water and has begun design and construction of the Santa Monica Urban Runoff Reclamation Facility (SMURRF). Perkins and Shapiro (2000) reported that the City of Santa Monica, California is using both a micro- and a macro-scale approach to watershed BMP implementation. Reuse of stormwater and treated sewerage effluent, previously regarded as waste, has begun in South Australia through the innovative aquifer storage and recharge technique. After pretreatment in wetlands, this water was stored in otherwise-unused brackish aquifers for summer irrigation of parklands. Barnett et al. (2000) presented several case studies where the aquifer storage and recharge technique has been successful, with savings in water and infrastructure costs, as well as providing environmental benefits. Domestic harvesting of rainwater as a source of water for flushing toilets and watering gardens was assessed in Berlin, Germany. Rainwater harvesting relieved demand on potable water supplies and rainwater drainage in Berlin's urban districts (Koenig 2000).

Urban streams are often badly degraded from their pre-development, natural state. Restoration of these streams is becoming a widespread practice, and is often done in conjunction with WWF control efforts. Athanasakes et al. (2000) described the holistic stream restoration program which was developed by the Louisville and Jefferson County, Kentucky, Metropolitan Sewer District. Their discussion focused on issues involved in developing and managing a streambank stabilization/stream restoration program, such as getting a program started, a brief overview of stream restoration techniques, items to consider during construction and a summary of items learned throughout the development of the program. Stormwater management in an urbanized basin near Dallas, Texas included channelization of a creek which was eroding private property (Amick 2000). Since the watershed was nearly fully developed, areas where mitigation could be accomplished were limited. Mitigation was required - leading to some restoration of another urban stream that had previously been channelized. The creeks in the Kelowna, British Columbia, Canada area, like those throughout North America, have been impacted by human development. The City of Kelowna initiated the Lower Mill Creek Watershed Program in 1997. Objectives of the program included (1) improvement of Mill Creek water quality by preventing streambank erosion and creating riparian areas; (2) restoration and enhancement of instream and streamside habitat; and (3) education of the public, private landowners and developers on the importance of Mill Creek (Gow and Kam 2000). The U.S. EPA has allowed local governments to establish natural vegetative buffers (greenways) along stream corridors in lieu of incurring other EPA enforcement actions associated with violations of the Clean Water Act. Kleckley and Kung'u (2000) identified the role of greenways in protecting water quality and aquatic and stream corridor habitats, and described an on-going greenways project in Jefferson County, Alabama. Rodriguez et al. (2000b) presented a pool-riffle design for straight urban streams where existing infrastructure has prevented channel planform re-alignment. The proposed structures fulfilled four main requirements: (1) increased flow variability during low and moderate flows; (2) produced minimal increase in the water levels during high flows; (3) self-maintained in terms of bed erosion and sediment deposition, and (4) provided in-stream habitat for fish. Von Euw and Boisvert (2000) presented two case studies that focused on the partnership process, design and implementation, and lessons learned from the construction of two riffle weirs in urbanized streams in Vancouver. Key conclusions were that partnerships are an effective tool for implementing

stream improvement projects in a cost-effective manner; and that riffle weirs can function effectively in an urban setting to mimic natural stream morphology, thereby improving fish habitat and channel stability.

Urban watershed managers are increasingly investigating stormwater control programs as a whole, rather than focusing on individual BMPs. Chocat et al. (2000) described the evolution of urban drainage, noting that even though urban drainage has been practiced for more than 5000 years, many challenges arising from growing demands on drainage still remain with respect to runoff quantity and quality, landscape aesthetics, ecology and beneficial uses, and operation of existing urban wastewater systems. In Lulea, Northern Sweden, Backstrom and Viklander (2000) investigated which integrated stormwater system components might be suitable in cold climate regions. The authors found that porous pavement, grassed waterways (swales, ditches), wet pond, and percolation basin were the most suitable integrated stormwater system components in cold regions whereas dry basin, stormwater infiltration surfaces, and stormwater reuse seemed to be less suitable. The Delaware Canal, a unique, 60-mile long, 167-year-old man-made waterway, was built and operated commercially to haul coal and other goods from Bristol, Pennsylvania to Easton, Pennsylvania. Environmental Liability Management, Inc. prepared a map of the Delaware Canal Watershed, analyzed potential strategies to reduce accelerated erosion and sedimentation in the canal watershed, and produced a report intended to educate local residents and township and county officials on land use/management practices that could be incorporated into local ordinance to reduce the excessive sedimentation in the canal (Brussock et al. 2000). Barrett (2000) discussed the potential for BMPs to adequately address receiving water impairments in southern California. He concluded that pollutant removal rates for conventional BMPs will not enable BMPs to reverse adverse receiving water impacts.

Several innovative watershed management approaches are attempting, in combination with a system of BMPs, to preserve the natural runoff-controlling features of a site. Low Impact Development (LID) is rapidly being recognized as an ecologically sustainable and cost effective strategy to protect receiving waters from the water quality, volume, magnitude, and frequency effects of stormwater runoff. The LID strategy is based on creating hydrologically functional equivalent design features that replicate the pre-development conditions through the use of pollution prevention, precision engineering, and integrated micro-scale BMPs throughout a site. Coffman et al. (2000) presented the management strategies, protocols, and technological approaches incorporated in the development of an LID management strategy for the control of WWF in urban areas. Two publications that describe LID are the *Low-Impact Development an Integrated Design Approach* and *Low-Impact Development Hydrologic Analysis* (obtainable from the National Service Center for Environmental Publications (NSCEP) 1-800/490-9198). Daniil et al. (2000) presented general design considerations and principles for flood protection and related stormwater design, based on an integrated environmental approach and involving less technical works and preservation of the physical condition of streams and creeks. The application of the above mentioned consideration was illustrated in two specific case studies from the suburbs of Athens, Greece. Hall and Scarbrough (2000) reviewed the development and implementation of new-development requirements aimed at watershed protection in Gwinnett County, Georgia, USA. The approach presented is simple to use and encourages site design that takes advantage of the natural site amenities and minimizes impervious surfaces. Kauffman and Brant (2000) advocated amending existing zoning codes to establish watershed-zoning districts based on percent impervious cover thresholds in the Christina River Basin of Delaware.

The Storm Water Phase II Rule, published in the Federal Register on December 8, 1999, will bring approximately 5,000 small municipal separate storm sewer systems (MS4s) and over 100,000 small construction sites into the National Pollutant Discharge Elimination System (NPDES) permitting program by 2003. USEPA is supporting implementation of this rule through the development of a 'tool box.' This tool box will consist of fact sheets, guidance, a menu of BMPs, an information clearinghouse, training and outreach efforts, technical research, support for demonstration projects, and compliance monitoring/assistance tools (Kosco 2000). The City of Portage, Michigan, pioneered a comprehensive approach to storm water management in light of the Phase II Storm Water regulations. The approach has served to define the application of the now elusive "Maximum Extent Practicable" (MEP). Breidenbach et al. (2000) presented the approach for selecting design parameters to define MEP and identified how the minimum control measures for Phase II regulations are incorporated into the passive storm water treatment system design.

Once a watershed management study has been conducted and a plan adopted, local planners and engineers are often faced with the questions of how to practically translate these recommended management strategies or best management practice recommendations into zoning and subdivision regulations, capital improvement plans, and assistance programs, how to encourage effective site design and also provide flexibility in meeting environmental objectives, and of finding a practical, economical way to track how the design and best management practices are performing. Brewer et al. (2000) documented Rockdale County's innovative Development Performance Review, including its procedures, and program

cost/staffing requirements. Fernando et al. (2000) described the development of effectiveness indicators for stormwater and watershed management programs and the development of a regional monitoring program. The study was conducted for the jurisdictions encompassed by the Hampton Roads Planning District Commission, with specific focus on the six cities that currently have Virginia Pollutant Discharge Elimination System stormwater permits. New Jersey developed a rule proposal to standardize its approach to the watershed planning process, and to goals and objectives for watershed planning. Van Abs (2000) proposed a conceptual basis for watershed planning objectives and thresholds, and then described how New Jersey's planning and regulatory system currently and prospectively addressed the issues. As part of the stormwater planning process for the Greater Vancouver area, a watershed classification system was developed to help evaluate the current and future impacts of stormwater discharges on the receiving environment. The system was designed to easily communicate these impacts along with potential mitigation strategies to stakeholders and decision-makers. Woods et al. (2000) described the watershed classification system, presented the classification results for 1996 and 2036, and outlined some of the experiences with developing and using this watershed management tool.

The California Department of Transportation (Caltrans) constructs, operates, and maintains the state highway system in California; the runoff from which is subject to the federal Clean Water Act and its associated NPDES permit program. New permit requirements have required methods that achieve higher levels of pollutant control than conventional BMPs. As a result, Caltrans initiated an extensive research and pilot-testing program to identify new technologies that can be used to meet water quality standards (Krieger 2000). Prior designs assumed that street drainage was designed to collect stormwater as fast as possible, and therefore, the street stormwater capacity was defined as its hydraulic conveyance and was estimated by Manning's formula. Guo (2000) found that the street stormwater capacity at a sump was actually dictated by the storage capacity rather than the conveyance capacity. A new design methodology was developed that considered the street depression storage as a criterion when sizing a sump inlet. In 1999, two oil-water separators at Mobil de Colombia's terminal facilities in Cartagena, Colombia were replaced in order to bring the facility into compliance with environmental law. Using a proprietary computer program it was found that the existing pits were large enough to meet the national environmental regulations for effluent oil content if fitted with multiple-angle coalescing plates. Gutierrez et al. (2000) presented the legal requirements, operating conditions, the new internals, and a discussion of how the new internals will affect the quality of the water exiting the facility. Patwardhan et al. (2000) briefly outlined the Best Management Practices (BMPs) and reporting modules of the Hydrological Simulation Program – FORTRAN (HSPF) model in relation to its application to the Camp Creek and Little River Watershed Assessment Project (Fulton County, Georgia).

Stovin and Saul (2000) described an extensive laboratory and computational fluid dynamics study into the hydraulic performance and sediment retention efficiency of tanks. The results showed that (1) using computational fluid dynamics, it was possible to predict the flow field that was measured in the laboratory, and (2) a critical bed shear stress could be used to determine the extent of sediment deposition. The study also showed that the length to breadth ratio of the chamber was the most important parameter to influence sediment deposition, and that changes to the benching and longitudinal gradient of the tank had minimal effect. Intensity/duration/frequency (IDF)-relationships of extreme precipitation have been widely used for design of stormwater facilities. Because the properties of extreme precipitation may be very different for different storm types and different seasons, IDF-relationships which permit decomposition into different components and scaling properties were established by Willems (2000). Hydrologically functional landscapes integrated principles of maximizing infiltration, contouring the landscape to encourage temporary detention, and the use of stormwater to reduce demand for irrigation water. Wright and Heaney (2000) reported on the design and monitoring of a hydrologically functional landscape in Boulder, Colorado, and presented a simulation that evaluated the performance of the system. Low Impact Development (LID), a micro-scale runoff control strategy for WWF, has been based on a combination of conservation to reduce hydrologic impacts and incorporation of distributed micro-scale BMPs throughout the subcatchment. LID has resulted in a need to develop new models or modify existing ones. Wright et al. (2000) explored the potential and limitations of existing models in order to evaluate the effectiveness of this design approach. An extensive review of some 50 designs for litter traps which are recommended for urban drainage designs indicated that only seven showed much promise for South African conditions. A preliminary assessment of the seven most promising trapping structures concluded that three designs - two utilizing declined self-cleaning screens and the other using suspended screens in tandem with a hydraulically actuated sluice gate - are likely to be the optimal choice in the majority of urban drainage situations in South Africa (Armitage and Rooseboom 2000a and 2000b).

According to Herr and Harper (2000), stormwater treatment using flow-weighted injections of alum achieved high removal rates of nutrients, heavy metals, and bacteria while proving to be an extremely cost-effective retrofit. Two case studies using alum injection in Florida were presented. A National Cooperative Highway Research Program-funded

research project was described by Stein et al. (2000) and included both a synthesis of current information and a plan to guide future research on management of runoff from surface transportation facilities. The issues to be studied included regulations and permitting, runoff water quality characteristics, best management practices, receiving water impacts, and habitat impacts. Insufficient space, high land values, topography, maintenance, aesthetics and liability issues were given as reasons why underground detention has been considered more frequently. Finlay (2000) presented the development of a computer program for designing underground stormwater detention tanks. The program had four main functions: (1) develop or allow the direct input of an inflow hydrograph, (2) size the structure and develop a stage-storage relationship, (3) design the release structure and develop the stage-discharge relationship, and (4) route the inflow hydrograph through the structure. Boyd (2000) presents a collection of pre-programmed hydraulic and hydrology-related functions that have been compiled as an add-on module for use in computer spread sheets to aid in BMP and urban drainage design. Results from the modules are similar to results given by widely-used modeling software.

BMP performance can be verified only through expensive field testing, making published testing results a valuable resource for planners and engineers. Strecker et al. (2000) reported on a research program funded by USEPA and ASCE to develop a more useful set of data on the effectiveness of BMPs used to reduce pollutant discharges from urban development. They described some of the comparability problems encountered between different BMP effectiveness studies, considerations that affect data transferability, such as methods used for determining efficiency and statistical significance, efforts used to establish and analyze the currently available data and proposes protocols for future analyses. The authors recommend that effluent quality would likely be a much more robust measure of BMP effectiveness and performance than the currently used "percent removal" metrics. Ball et al. (2000) evaluated the effectiveness of stormwater treatment devices installed on a roadway in Australia, including detention tanks, a Continuous Deflective Separation (CDS) GPT, and a sand filter. It was concluded that the devices were improving the quality of stormwater flowing from the road drainage system into the general catchment stormwater system. Greb et al. (2000) evaluated the water-quality benefits of a new urban best management practice design called the multichambered treatment train. High reduction efficiencies were found for all particulate-associated constituents, such as total suspended solids (98%), total phosphorus (88%), and total recoverable zinc (91%). Dissolved fractions had substantial but somewhat lesser removal rates (dissolved phosphorus, 78%; dissolved zinc, 68%). The Washington State Department of Ecology's efforts to reduce the flow of pollution to Commencement Bay sediments, a federal Superfund site, caused metals concentrations in the bay to decrease by a factor of 10 between 1984 and 1997. This accomplishment demonstrated that major water quality improvements were possible in a heavily industrialized area (Smith et al. 2000c). Wang et al. (2000) sampled stream physical habitat, water temperature, and fish and macroinvertebrate communities at multiple paired watersheds in Wisconsin before and after BMP installation from 1993 to 1999 to examine the responses of stream quality to watershed-scale BMP implementation. Results clearly demonstrated that watershed and riparian BMP implementation improve overall stream quality. A CDS unit would be expected to separate the following pollutant loads from a stormwater system: suspended solids, bed loads, floating solids, free oil & grease. Field studies verified removal efficiencies for gross solids to be greater than 95%, with particulate phosphorous removal of greater than 30%, and TSS removals greater than 70% (Kohzad 2000).

Non-structural BMPs, such a reduction in the use of pesticides and fertilizers, often have been suggested for WWF control; however it is often difficult to assess the impact of such BMPs. A project in Sydney, Australia assessed the effectiveness of a directed community education program for non-structural management at stormwater sources through detailed monitoring of both the community and the stormwater volume and contamination. Ball et al. (2000) outlined how the community education program focused on issues of concern to the local community and how changing practices could impact the problem. Also outlined were the monitoring program developed to evaluate the effectiveness of the program and the availability of stormwater contaminants. Henning (2000) outlined the development and work of "WaterShed Partners," a coalition of more than 40 public, private and non-profit organizations in the Minneapolis/St. Paul, Minnesota metropolitan area. "WaterShed Partners" developed and implemented a variety of public education programs to educate the public about changing household behaviors such as water usage, lawn care practices and proper disposal of household hazardous waste.

The pollutant loads conveyed by street cleaning waters, by street runoff and the maximum pollutant load removed by street washing were measured for three streets in central Paris, France. For suspended solids and organic matter, the pollutant load removed on a daily basis from street surfaces by street cleaning waters was found to be similar to that removed during one rainfall event. However, it was five times lower for heavy metals. It was also shown that the total mass of pollutants stored on the street surface is significant, and that the effects of street cleaning may be limited. An unexpected effect of street cleaning was found - it induces sediment erosion inside the sewer during dry weather periods,

thus reducing the stock of pollutants available for wet weather flow (Gromaire et al. 2000).

Current turfgrass management practices in the U.S. have contributed to environmental problems, generated large amounts of solid and hazardous waste, and used large amounts of water during the summer months when fresh water supplies are lowest. These practices, including home lawn care, have included intensive use of water-soluble fertilizers, herbicides, insecticides, and fungicides, which may be harmful to human health and to aquatic ecosystems. McDonald (2000) presented an alternative approach based on observation of the entire soil and grass ecosystem, appreciation that turfgrasses are sustained by the activities of soil-dwelling organisms, and understanding that this grass community is a dynamic equilibrium among many plants, invertebrates, and microbial organisms. Pauleit and Duhme (2000) developed a method to delineate urban land cover units to establish the relationship between, on one hand, the socio-economic performance of the urban system and its different sub-units (i.e. housing schemes, commercial and industrial developments, services), and on the other, the environmental impacts of these sub-units. A case study on urban hydrology was presented to characterize aspects of the metabolism of the urban system. A multi-stakeholder group, was formed to address and to remediate nonpoint sources of bacteriological pollution threatening the economic and environmental health of Baynes Sound, Vancouver Island, Canada. This work demonstrated that partnerships among government, the shellfish industry, community groups, and citizens can create a powerful force for improving water quality (Pinho 2000). The University of Connecticut Nonpoint Education for Municipal Officials (NEMO) Project developed an educational program targeted at land use decision-makers. The program emphasized natural resource-based planning that prioritizes local natural resources and finds a rational balance between development and conservation. Four simple elements are shared by projects in the group: (1) an educational approach, (2) an emphasis on land use education, (3) a focus on land use decision makers as the target audience, and (4) the use of geospatial technology in the service of education (Rozum et al. 2000).

According to Strecker et al. (1999), the EPA cooperative research program with the American Society of Civil Engineers (ASCE) developed a more useful set of data on the performance and effectiveness of individual BMP and to assess the relationship between measures of efficiency and BMP design. BMP monitoring data should not only be useful for a particular site, but also be useful for comparing studies of similar and different types of BMP in other locations. It suggested some of the ways that data should be collected to make it more useful for assessing factors (such as settling characteristics of inflow solids and physical features of the BMP) that might have led to the performance levels achieved. It recommended efficiency calculation methods and appropriate terminology to be used in evaluating BMP assessment studies. In addition, Clary et al. (1999) stated that the National Stormwater BMP Database included test site location characteristics, sponsoring and testing agencies, watershed characteristics, BMP design and cost data, monitoring locations and instrumentation, monitoring costs, precipitation data, flow data, and water quality data. The data retrieval, or search engine, portion of the software enabled users to retrieve BMP data sets based on a variety of search criteria such as geographic location, watershed size, BMP type, and water quality parameters.

Ecotechnology was the use of technological methods for environmental management in a way to minimize the harm to the environment. Herein the primary contributors to NPS pollution were presented. Best management practices (BMP) for NPS pollution were reviewed, and ecological engineering measures for NPS control were described and evaluated (Dermissi et al., 1999). stormwaters flow directly into the Matajoki River, which was situated in Southern Finland with a catchment area of 24.4 km², was monitored with a limnograph. Separate sewage systems were present throughout the catchment area; domestic sewage was directed to a sewage plant directly outside the catchment area. During the research period July 1, 1995 to June 30, 1996, water samples from the Matajoki were taken at least weekly (Olli, 1999).

According to Rushton (1999), an innovative parking lot design at the Florida Aquarium in Tampa, Florida, was being used as a research site and demonstration project to show how small alterations to parking lot designs can dramatically decrease runoff and pollutant loads. Three paving surfaces were compared as well as basins with and without swales to measure pollutant concentrations and infiltration. Utilization of parking lots around Hattiesburg, Mississippi was examined to suggest mechanisms for reducing runoff into local streams (Albanese and Matlack, 1999).

Prince George's County, Maryland first introduced the bioretention device (commonly referred to as a "rain garden") in 1990. Utilizing physical, chemical, and biological treatment processes within an aerobic soil media/vegetated filter system, bioretention has been shown to be highly effective in removing pollutants such as heavy metals and nutrients from urban runoff. By capturing, infiltrating or filtering stormwater runoff close to the source, the use of bioretention treatment can also restore hydrologic functions (Winogradoff and Coffman, 1999). Beginning in July 1997, the University of Virginia has been testing a vault/reservoir structure installed at a bus maintenance facility in Charlottesville, Virginia;

two larger such structures were later installed in Warrenton, Virginia and were monitored between October 1997 and September 1998. Another ultra-urban BMP, a bioretention area, was installed at a high school site in 1998 and has been monitored since November 1998. A total of 22 storm events were sampled at the vault/reservoir structure sites, and 4 storms have been sampled at the bioretention site; water quality parameters examined included total suspended solids (TSS); total phosphorus (TP); chemical oxygen demand (COD), and oil and grease (OG) (Yu et al., 1999).

No single BMP will prevent all the effects on receiving waters caused by urban runoff, however, through a combination of source and treatment controls, the greatest benefits will be gained. Stormwater management objectives should focus on obvious localized problems for near-term goals and should establish an appropriate scientific and administrative structure for addressing long-term beneficial use protection in a cost-effective manner (Joint Task of WEF and ASCE, 1998). A BMP screening procedure was used to develop a watershed plan for the Bear Creek part of the Clinton River Watershed in southeast Mich. (Paluzzi and Ditschman, 1998). The screening procedure assessed water-quality sampling and habitat inventory, physical suitability, stormwater benefits, pollutant removal, environmental amenities, and institutional constraints and costs. A linear program, which was developed and run on commonly available spreadsheet software, optimized the selection of BMP for a watershed (Lewis, 1998). O'Leary and Clevenger (1998) reviewed the Maryland Department of the Environment's past and present stormwater regulations and plans for a new design manual. De Hoop et al. (1998a) reported the results of a survey of log storage yards in La. that gathered information related to stormwater runoff such as storage practices, soil composition, materials stored, and runoff control practices.

Silt fences removed sediment from runoff at a construction site in Austin, Tex. by particle settling, not filtration and were ineffective in reducing turbidity (Barrett et al., 1998b). Mean sediment removal efficiencies in flume studies ranged from 68—90%, depending on detention time of the runoff, however, large quantities of construction sediment remained in the discharge because initial sediment concentrations were 3 000 mg/L or more. Dee et al. (1998) reported on efforts by the Virginia Department of Transportation to help protect the water quality of the reservoir before, during and after construction of a roadway project located within the Rivanna River Reservoir watershed. The benefits provided by porous and permeable pavements over the last 20 years included flow attenuation, aquifer recharge, pollution control and treatment, stored water reuse and effluent quality enhancement. These pavement have also provided evidence of their sensitivity to environmental factors and changes over time (Pratt, 1998).

Several sources addressed a "new technology" in BMP - Low Impact Development (LID). By reducing the change in curve number (CN), maintaining the pre-development time of concentration (T_c), incorporating distributed retention and then, if required, adding detention BMP to maintain the runoff volume and peak runoff rate, (Coffman et al., 1998a, 1998b, and 1998c) LID creates a "functional landscape" that incorporates design features that mimics pre-development, natural watershed hydrologic functions. Runoff may be reduced and controlled at the site by minimizing impacts to the extent practicable by reducing imperviousness, conserving natural resources, recreating detention and retention storage, maintaining pre-development T_c by strategically routing flows to maintain travel time, and implementing effective public education programs that encourage property owners to use pollution prevention measures. Net results for LID stormwater treatment and management mimic the water balance between runoff, infiltration, storage, groundwater recharge, and evapotranspiration (Dep. Environ. Resour., Prince George's County Md., 1997). LID techniques integrate stormwater controls in small discrete units throughout the site. Distributed BMP reduce the need for a centralized BMP facility. Micro-management of stormwater, which has been used successfully in several communities, stores water temporarily at many locations on and off the street and below the surface and as close as possible to the precipitation source prior to entry into a combined, sanitary or storm sewer system (Carr and Walesh, 1998). Bioretention uses plants and soil to filter runoff from developed areas. Laboratory and field tests showed good removal of metals, P, and NH_3 with little or negative removal of nitrate. A significant mulch layer was found to be important for metals removal (Davis et al., 1998b).

Within the 16.2 ha (40 acre) festival grounds in downtown Milwaukee, Wis. a flow splitter diverted the first flush stormwater from a 1.2 ha (3 acre) area to a constructed landscaped island with a layer of peat over a layer of fine sand and at a hospital in Green Bay, Wis., a pressurized two stage filter system was designed to reduce pollution from a 2.6 ha (6.5 acre) parking lot (Bachhuber, 1998). A swale-infiltration trench system that combined three engineering techniques (infiltration, storage and throttled drainage) to manage rainfall runoff can be applied to new developments or as a retrofit (Sieker, 1998). Urban stormwater was treated by a combination of engineered and natural treatment systems comprised of a wetland perimeter swale and a berm which directed collected surface water runoff to a 30 m wide forested wetland filter strip (Berg, 1998). A sand-filter system and two grassy medians located on highways near Austin, Tex. were evaluated (Barrett et al., 1998c). The grassy areas reduced SS by 85% while the sand filter reduced pollutants by 90%, but was plagued with maintenance problems and detention times exceeded the 48 hour design. The capability of vegetated

highway medians for treating stormwater runoff in the Austin, Tex. area was studied by examining pollutant removal efficiencies of two medians on major highways. Removal efficiencies at the two sites were remarkably similar despite being designed solely for stormwater conveyance and differed in slope and vegetation type and were comparable with those observed in structural controls such as sedimentation/filtration systems (Barrett et al., 1998d).

Washington, D.C. required that BMP be required for new and re-development projects to control urban-stormwater-runoff pollution. Dee (1997) retrofitted an existing drainage basin with a sand-filtration system that controlled the 2-yr and 15-yr rainfall events. An innovative BMP system for a recreational farm in Taiwan was evaluated by Wen and Yu (1997). The BMP system included a grassed strip, a swale, wetland vegetation, two check dams, a shallow lotus pond, and two wet-detention ponds. The results indicated that BMP put in series could provide high pollutant removal, especially for particulates. According to Pechacek *et al.* (1997), key components of BMP include good-housekeeping procedures; preventive-inspection and maintenance schedules; management strategies to prevent contamination of stormwater runoff; facilities that manage runoff to prevent contact between pollutants and runoff; and facilities that reduce pollutants in the runoff. U.S. EPA (1997d) addressed some of the unique challenges for designing BMP in cold climates.

Barrett *et al.* (1997) evaluated different types of structural BMP systems for treating highway-stormwater runoff, including grassy swales, extended detention ponds, and sedimentation-filtration systems. As a part of stormwater management BMP, the Maryland Department of Environment applied a groundwater-syphon system to mitigate wet-pond-outflow temperatures in order to comply with the State's threshold criteria for stream-flow temperatures (O'Leary, 1997). A literature summary documented the benefits analysis associated with an alternative development approached for controlling stormwater runoff (U.S. EPA 1997e). The Baltimore County, Department of Environmental Protection and Resource Management developed a stormwater-management-water-quality-retrofit program to improve BMP performance in an urbanized environment. O'Leary *et al.* (1997) reported the program details, including assessment of water quality, BMP-retrofit options and prioritization, feasibility and cost effectiveness, and aesthetics and neighborhood acceptance.

Livingston *et al.* (1997a and 1997b) developed two separate reports to address institutional aspects of urban-stormwater-runoff management and the operation and maintenance of stormwater-management systems which included sample stormwater-management-inspection forms.

General stormwater control objectives and sustainable drainage design.

Braune and Wood (1999) described how South Africa currently has one of the highest rates of urbanization in the world, causing a significant increase in surface water runoff and attendant increases in flooding and significant decreases in water quality. They presented a method of how the existing problem areas can be identified and ranked, and how the use of BMP can be used to reduce the impacts associated with urbanization. Cutler and Eastman (1999) described two projects in Christchurch City, New Zealand. The first, Regents Park, was an urban subdivision in an area with springs, open drains and a high water table. The City Council worked with the developer to naturalize and enhance the open waterways so that they added value to the landscape, ecology, drainage, and value of the subdivision. The second area, the Tranz Rail transfer yards, was a multi-million dollar development involving extensive areas of roofing and paved surfaces. They developed an integrated stormwater design approach that includes a two-stage settling/treatment/filtration system that retains peak discharges, contains contaminated spills, and alleviates downstream flooding. Hottenroth et al. (1999) examined the effectiveness of integrated stormwater management in Portland, Oregon. The stormwater program encourages innovative, non-structural pollution reduction techniques such as native landscaping, grass swale drainages, ponds, and public involvement and education. The Parkrose Pilot Project was started in 1994 to test the effectiveness of a wide range of these BMP in a small watershed in north Portland.

The Auckland Regional Council (ARC), New Zealand published a manual for design of stormwater quality improvement devices (TP10). Within that manual a modified Rational Method was used for flood estimation. An improved method was developed for estimation of storm runoff to represent the effects of different approaches to land development, including the use of different types of land cover and drainage systems, which could significantly modify the volume, timing and peak rate of runoff (Levy and Papps, 1999). The ARC developed a manual "Low Impact Design for Stormwater Management" (Shaver, 1999). Schueler et al. (1999) described a series of 22 land development principles developed by a consortium of American planning, road, banking, engineering, development and public safety organizations. The environmental impact assessment database being developed for Project Storm consists of a ranking system to provide comparative data for aquatic resources in terms of existing natural environmental values and existing effects (Stevens et al., 1999).

Iwamoto et al. (1999) described the sequence of urbanization, and associated receiving water problems in Japan. River excavation and widening were first used in the suburbs, followed by the raising of levees and overflow spillway to let flood discharges flow into temporary storage areas near rice fields. In the most urbanized areas, drainage channels and pump stations were constructed to handle the increased flows. Contrary to these historical approaches, they feel that “soft” approaches should be tried to encourage the natural benefits associated with reforestation and land consolidation. Kobayashi (1999) described changes that have occurred with development in Nagoya City, Japan. Rapid rainwater conveyance was being achieved by expanding storm sewers and pumping stations, but they were also stressing the use of infiltration facilities throughout the city area. Private infiltration facilities have not been developed as much as they hoped. The authors described an approach to constructing porous pavements; managing the decreased infiltration capacity of the pavements with time; and the needed field inspection and recovery operations to restore the infiltration capacity.

Cutler and Simpson (1999) described the challenge facing the city of Christchurch (New Zealand) to develop sustainable, aesthetically pleasing waterway environments that were environmental assets for the adjacent landowners. Designers were expected to naturalize the artificial drainage channels, or create new realigned reaches in confined urban settings. A range of techniques were being applied to replace the existing drainage system with a sustainable naturalized waterway environment. Stahre (1999) reviewed ten years of different experiences pertaining to sustainable stormwater management in the city of Malmö, Sweden. A basic element in sustainable stormwater management in Malmö was the involvement of ecological processes in drainage and that the technical design, to a great extent, was adapted to the prevailing local conditions.

Zhang et al. (1999) stated that, although separate sewer systems usually were not designed to take full advantage of available NPS controls, a great improvement can be achieved by combining a number of separate control options. Thorolfsson and Sekse (1999) reports that the green trend in urban stormwater management, as demonstrated in the Birkeland test basin in Bergen, Norway, utilizes the capabilities of nature to store huge stormwater and snowmelt volumes and to reduce the pollution content in the receiving water. Thorolfsson (1999a) further described the Sandsli system (an alternative drainage system demonstrated in Bergen, Norway) used for drainage management in the north Atlantic. The goal was to manage the total urban runoff (wastewater, stormwater, and snowmelt) in a way that environmental damage was avoided, and the goals for the receiving water were achieved at reasonable costs. Thorolfsson (1999b) described how non-contaminated runoff was to be handled near the source by percolation and/or detention, while the polluted runoff will be collected and conveyed to an appropriate site for treatment and discharge.

McAlister et al. (1999) found that the fine sediment in urban stormwater was a key cause to many receiving-water impacts. As a consequence of these studies, a total catchment approach has been developed and applied to urban stormwater quality management in Brisbane city (Australia). Mehler and Ostrowski (1999) found that an economically and ecologically sound combination of centralized and source area control measures will be a concept of the future of stormwater management in Germany and elsewhere. Holz (1999) described how engineering solutions have not been effective at avoiding the degradation of receiving waters in the northwest of Washington’s Pacific coastal region. They concluded that “hard” engineering methods have little chance of mimicking the stormwater runoff attenuation of forest cover, regardless of storage provided, and that another paradigm for development must be adopted (in contrast to the present “clear, grade, and pave” approach that has not been proven to be mitigatable).

BMP effectiveness.

Roesner and Brashear (1999) reported that over the last ten years, a number of BMP manuals have been developed to address the control of urban runoff for receiving water quality protection. They concluded that there was a lot of ignorance in the scientific community about what constitutes a properly designed BMP and what it really achieves, with respect to environmental protection. They therefore recommend a design criteria development approach that can be applied over a wide variety of climatologic, topologic, and geologic conditions to protect receiving waters systems. Roesner (1999) further believes that the conflicting opinions on the effectiveness of various BMP result mostly from: 1) there was no accepted uniform design criteria for BMP; and 2) the objectives of the management practices differ between authors.

Buffer corridors. Crifasi (1999) gave a description of Boulder’s (Colorado) instream flow and riparian zone management program, where extensive, high-quality wetlands and riparian areas exist along south Boulder Creek. South Boulder Creek’s riparian corridor contains plains riparian cottonwood forests, willow shrublands, freshwater marshes, and alkali wetlands that provide refuge for two federally threatened species, plus other rare species of plants and animals.

Haberstock (1999) presented a method used to determine optimal riparian buffer widths for Atlantic salmon habitat protection in Maine. Zone 1 (no-cut zone), closest to the stream, has a fixed width of 35 ft in which no disturbance to soils or vegetation should occur. Zone 2, landward from zone 1, was a variable width zone where only limited uses that do not compromise the desired functions of zone 2, such as light tree harvesting and light recreation, should occur. Resulting total optimal buffer widths (zone 1 plus zone 2) range from a minimum of 70 ft to a maximum of more than 350'. In rare cases (e.g., extensive slopes > 25%), optimal buffer widths can be 1,000 ft or more. The rehabilitation of urban stream channels to protect Pacific Northwest salmon runs were described by Henshaw (1999). In an effort to bolster the survival of salmon returning to the local streams to spawn, land managers have begun extensive programs to rebuild or rehabilitate appropriate habitat that has been lost or degraded due to urban development. Although rebuilt habitat in a stabilized urban stream may not provide the level of ecological integrity required to maintain endangered salmon and other stream biota, physical stability was likely one necessary component of a healthy stream. O'Neal et al. (1999) described hydraulic and biological effects of large woody debris (LWD) and an engineered wood alternative for stream channel rehabilitation projects in the state of Washington. The engineered structures consist of an interlocking complex of small diameter poles that can be carried by hand and assembled on site. The artificial structures have a high hydraulic and surface roughness to trap sediment and debris and caused variations in the pattern of water flow and resultant scour compared to natural LWD. No statistically significant differences were observed in the biological communities associated with these structures compared to LWD.

The city of Austin, Tex. Stormwater Monitoring Program (Glick et al., 1998) monitored various types and designs of BMP over a 15 year period and concluded that large regional water quality BMP tended to be more cost effective even if the treatment efficiencies are moderate because they can treat more runoff. The cost differential indicated that large systems (e.g., wet ponds) may be a more cost-effective option for areas being retrofit with BMP. Alum proved to be the most effective coagulant for stormwater runoff at Mosquito Lagoon located in New Smyrna Beach, Fla. when tested against ferric chloride which was not effective at enhancing settling (Escobar et al., 1998).

Stormwater reuse.

Argue and Pezzaniti (1999) investigated the harvesting of stormwater to replace water supply mains for the irrigation of areas landscaped with grass, flowerbeds, and shrubs in Adelaide, South Australia. Four categories of catchments were recognized according to their levels of pollution production - roof runoff and "low", "medium" and "high" pollution runoff surfaces. Large roof areas draining to gravel-filled trenches provide passive irrigation for grassed surfaces, for example. Dillon et al. (1999) described the development of "new" water resources by using aquifer storage and recovery of stormwater. The reuse of reclaimed water through storage aquifers can lead to more environmentally sensitive design, with reduced requirements for imported water, reduced exports of sewage and stormwater, and lower water supply costs. Dixon et al. (1999) demonstrated the water saving potential of domestic water reuse systems using greywater and stormwater. Monte-Carlo modeling results show that changes in household occupancy, roof area, appliance type, and storage volume, affect the water saving efficiency of a reuse system. Fox (1999) also described a watershed approach for integrated water reuse. Zaizen et al. (1999) described roof-runoff reuse at domed stadiums in Japan, as part of a wider program for preserving hydrologic cycle characteristics in urban areas. Tada et al. (1999) investigated three alternative storage methods that can be used to assist stormwater reuse. The best method (Type-1) uses a small tank to separate "first-flush" runoff nonpoint pollution loads from the remaining discharges. Type-2 has an overflow weir to separate polluted runoff stormwater, while type-3 has an orifice to separate un-polluted stormwater into the utilization tank. Pratt (1999) described the use of storage reservoirs under permeable pavements for stormwater treatment and reuse. Permeable surfaces for roads and footpaths have been used as a means of disposal of stormwater in developed urban areas and undersealing them to enable them to retain stormwater for reuse for non-potable uses was feasible. However, the stormwater may be degraded where the pavement was used for car parking. Tredoux et al. (1999) described the Atlantis Water Resource Management Scheme that uses artificial recharge of urban stormwater and treated wastewater to augment natural groundwater. The important element was the separation of the stormwater into components of distinctly different quality. Residential and industrial urban runoff was separated into baseflow and stormwater components and utilized for various appropriate purposes.

Public education.

Mashiah et al. (1999) found that raising community awareness of stormwater impacts was a critical component of an effective stormwater management program. The campaign included television advertising, newspaper and radio advertisements, displays, free environmental audits for local businesses, and a stormwater ambassador program for local schoolchildren. Heremaia (1999) described the public stormwater education program used as part of the Christchurch (New Zealand) integrated environmental planning program. The successful pilot program included the development of a

web site, audio conferences, a competition, and a drama production. Young and Collier (1999) described the research-based stormwater education of the New South Wales (Australia) Environment Protection Authority. This education program was unique in Australia by providing a comprehensive, integrated, and continuing research-based strategy for involving the community in preventing stormwater pollution.

The needs for linking local-economic and water-pollution problems were discussed from an urban perspective, including (1) access to information, (2) communication and outreach efforts, and (3) advocacy (Alex-Saunders, 1996). The EPA sponsored a number of local public-education programs for cities in abating WWF pollution (Austin *et al.*, 1996; Feuka, 1996). A multimedia public-information campaign helped achieve a 40% reduction of nutrients entering Chesapeake Bay (Leffler and Flagle, 1996). A multilevel cooperative-extension program including workshops, volunteer lawn, and master gardener lawn demonstrations was developed for the education of control of residential-nonpoint-source pollution. A community-action guide on environmental-restoration projects addressing citizen-volunteer participation and methods on how to organize restoration events resulted in a 100% positive experience in Chesapeake Bay areas (LeCouteur and Greenfeld, 1996).

Two new publications that address the causes and problem areas of SSO were released by the EPA (1996a and 1996b) for public awareness.

Public Works Practices

Catchbasins/grit traps

Grey *et al.* (1999) summarized the role of catchbasins in the CSO floatables control program in New York City. There were approximately 130,000 catchbasins, distributed over 190,000 acres, in New York City. They found that catchbasins were simple and very effective in controlling floatable material at the source. The most important aspect of catchbasin designs for floatables removal was the presence of a hood that was hung over the basin's outlet. Several studies conducted in the City have shown floatable retention efficiencies of 70 to 90%. Catchbasin hoods were also very cost-effective controls at a cost of about \$100 per acre. The City implemented a catchbasin inspection, mapping, cleaning, and hooding program as part of its CSO control program. Siegel and Novak (1999) reported on the activity of the microbial larvicide VectoLex CG (R) (*Bacillus sphaericus*) for the control of mosquitoes in 346 tested Illinois catchbasins. The tests were deemed successful.

Washbusch (1999) reported on an extensive evaluation of a proprietary urban stormwater treatment unit (the Stormceptor) in Madison, Wisconsin, conducted by the United States Geological Survey (USGS) and the Wisconsin Department of Natural Resources (WDNR). The evaluation was conducted on a 4.3 acre city maintenance yard site over 9 months and for 45 runoff events having rainfall depths ranging from 0.02 to 1.31 in., plus some snowmelt influence from imported snow to the maintenance yard. About 90% of the runoff was treated by the unit, and the remainder flows bypassed the unit during periods of high flows. The overall effectiveness of the unit was 33% for suspended solids, 17% for total phosphorus, 34% for total PAH, and from 20 to 30% for most heavy metals. In general, dissolved constituents were unaffected by the unit. Performance during the early spring events was degraded by high saline snowmelt water, which had elevated conductivity from on-site deicer storage, that significantly slowed particle settling.

Treatment of stormwater runoff from the recently constructed convention center on the shore of Lake Monona in Madison, WI, has recently been achieved with the installation of two vortex separators. The systems were designed to remove >80% of sediments and oils at flowrates of up to 0.48 m³/sec (17 ft³/sec), with peak 25-year flows of 1.27 m³/sec (45 ft³/sec) and 1.7 m³/sec (60 ft³/sec) anticipated at the two system locations (American City & County, 1996a and 1996b).

Litter/floatable control

Armitage and Rooseboom (1999) summarized the results of three years of laboratory investigations sponsored by the Water Research Commission of South Africa into the movement of urban litter through potential trapping structures. They found that once the litter has entered the drainage system it was difficult to remove. They concluded that declined self-cleaning screens showed the greatest promise for the removal of urban litter from most stormwater conduits and streams in the less developed countries. Newman *et al.* (1999) reported that the City of New York has improved its ability to control one source of floatables and possibly other pollutants to New York Harbor through its newly implemented "Illegal Dumping Notification Program." This program takes advantage of one City Department's field presence to gather and transmit valuable information to another City Department for enforcement and cleanup. They found that this program likely will reduce the number of illegal dumping sites by 15%. Phillips (1999) described how the State Government of

Victoria (Australia) provided funding to develop a litter trap (the In-line Litter Separator, or ILLS). The ILLS can be retrofitted into the drainage system downstream of shopping areas.

Two proprietary stormwater control devices were placed at drainage inlets and their performance compared with that of a conventional catchbasin inlet (Pitt and Field, 1998). No significant removals were found in the field tests of the proprietary devices, though large debris was trapped by one device, and a catchbasin retrofitted with a sump provided good removal of pollutants. A NYC study indicated street litter is a major contributor of floatables to N.Y. Harbor (Grey and Oliveri, 1998). Hooded catchbasins were 80—90% effective in retaining floatables and a city-wide program to inspect, map and hood all catchbasins was reviewed. Based upon a detailed examination of 18 facilities in Ger., Can., and U.S., Pisano et al. (1998) reported the performance of two widely used sewer and tank flushing technologies, i.e., the tipping flusher and the flushing gate.

Infiltration and Biofiltration, including Grass Swales and Grass Filter Strips

Ellis (1999) described the benefits and problems associated with directing roadway runoff to a roadside swale/infiltration system. He summarized the range of pollutant removal efficiencies achieved by vegetative BMP and reviewed available design procedures for grass-lined swales and constructed wetlands for the United Kingdom. Gharabaghi et al. (1999) described how rolled erosion control products have proven to be successful in reinforcing vegetative channel lining systems and improving their performance in erosion and sediment control. Mendez et al. (1999) summarized the results from an 18-month field experiment that was conducted to evaluate the effectiveness of grass filter strips in removing sediment and various nitrogen species from runoff. They found that the grass filters reduced contaminate yields from 42 to 90% and concentrations from 20 to 83%, depending on length and nutrient specie. Boubakari and Morgan (1999) tested the effectiveness of growing *Festuca ovina* and *Poa pratensis* on contour grass strips for erodible sandy loam soil on steep slopes. The *Poa pratensis* was less rigid and became flattened under submergence in the later part of the storms and was therefore not very effective in controlling erosion on the steepest slope tested (29%).

The effectiveness of grass strips in controlling highway-runoff contaminants was studied by Newberry and Yonge (1996). The largest portion of metals was found to be retained within the first 1 m of grass strip and 10 mm of depth, with 84% of the applied Zn, 93% of Pb, and >99% of Cd and Cu being retained by the grass strip. Pratt (1996) described recent research into design approaches for sizing of infiltration areas, illustrated the seasonal variability and difficulties in determining soil infiltration rates, and assessed the cost implications of alternative designs.

Infiltration

Ellis (2000b) addressed the potential conflict between the benefits of groundwater recharge of stormwater runoff versus the risks of long-term groundwater pollution in this paper. The long-term performance of a number of infiltration systems was reported in terms of their pollutant removal efficiencies, and the usefulness of an infiltration acceptability matrix approach was reviewed. Pitt et al. (2000a) presented a review of the literature available on the potential for groundwater contamination from the infiltration of stormwater runoff. The results on both the frequency and mobility of the potential contaminants was organized into a methodology that allowed evaluation of the potential contamination based on these two parameters. Part of this analysis included evaluation of the effects of infiltration on pollutant removal from the percolating water.

Nakazato (2000) presented a manual developed by the Japan Institute of Wastewater Engineering Technology on the technical issues faced by infiltration facilities. The objective of the manual was to clarify the definition of these facilities for stormwater management planning, and to promote the use of these facilities throughout Japan. The manual covers all phases of infiltration facilities through siting, design, installation and maintenance.

Morris and Stormont (2000) showed that near-surface processes such as precipitation, runoff, snowmelt and evapotranspiration have a significant impact on moisture movement in soils, and that models must include these near-surface processes. Pitt and Lantrip (2000) examined the effects of urbanization on soil compaction and resulting infiltration capacity through a series of double-ring infiltrometer tests. They found that sand was mostly affected by compaction, with little change due to soil-water content levels. However, the clay sites were affected by a strong interaction of compaction and soil-water content. The fit of the data to the Horton equation was inconclusive, indicating that when modeling runoff from most urban soils, assuming relatively constant infiltration rates throughout an event, and using Monte Carlo procedures to describe the observed random variations about the predicted mean value may provide the best results. Pitt, et al. (2000b) argued that if the traditional design equations were going to be used to predict infiltration, local data must be obtained and used.

Reemtsma et al. (2000a), in their study on the infiltration of combined sewer overflows versus tertiary-treated municipal wastewater, found that, when looking dissolved organic compounds, the groundwater quality that results from infiltration of CSOs is comparable to or better than the quality after infiltration of tertiary-treated municipal wastewater. However, the nutrient quality of the CSO water was worse compared to the tertiary-treated municipal wastewater after infiltration of both. Desorption of both nutrients and organics previously adsorbed was seen to be a potential problem of long-term infiltration. They also investigated the metals content of infiltration water from these two sources and the retention of these metals in the soil profile (Reemtsma et al. 2000b). They found that the metals were effectively retained during passage through the soil; however, additional alkalinity was needed to buffer the acidity caused by bacterial nitrification and mineralization, since soil acidification likely would result in both a reduction in efficiency of metals removal and a potential release of previously-trapped metals. Singh et al. (2000) investigated the potential for metals release from dredged-sediment-derived surface soils in the Netherlands. The authors found that runoff rates and sediment yields were highest for a silt loam sediment. The metals content of both the runoff and percolating water was greater than the standards for groundwater quality and very high metal fluxes were observed for the recently-oxidized dredged sediment. Metals transport per unit surface area was found to be two to twenty times greater for the percolating water when compared to the runoff water.

Backstrom and Bergstrom (2000) investigated the impact that snowmelt and temporary freezing conditions would have on the infiltration capacity of porous asphalts. Their results showed that alternate freezing and thawing conditions (similar to times of snowmelt) would reduce the infiltration capacity of the asphalt by 90% to a level of approximately 1 - 5 mm/min. Westerstrom and Singh (2000) investigated the infiltration of snowmelt runoff in Lulea, Sweden, and found that unlike rainfall infiltration, the snowmelt infiltration resembled a flow hydrograph, i.e., there was a distinctive rise, peak and recession to the graph. Unlike the relationship for rainfall and infiltration which is decidedly non-linear, a strong linear relationship between the snowmelt runoff hydrograph peak and the amount of snowmelt was found.

The use of filtration media for stormwater runoff treatment was investigated by several groups of authors. Brown (2000) investigated the potential for using kudzu to remove heavy metals from dilute aqueous streams, such as stormwater runoff. Kudzu was found to be an effective adsorber for heavy metals, and while its capacity was lower than that of commercial-grade resins, it was also cheaper than the resins. The application of kudzu to stormwater runoff was found to be particularly attractive both because of the cost and because of the potential problem of premature fouling of an expensive resin. Clark et al. (2000) investigated the potential of using low-cost adsorbents, such as peat moss and municipal leaf compost, to treat dilute aqueous wastestreams of copper such as stormwater runoff. The capacity of these adsorbents was compared to the capacities of other well-known adsorbents, such as activated carbon, bone char and cation-exchange resins. The low-cost adsorbents had removal capacities of approximately 20 - 30 mg Cu/g media. While these capacities were less than those of the bone char and resin (approximately 90 mg Cu/g), their cost was significantly less, and they demonstrated a robustness for dealing with the intermittent flow and potential interferences of stormwater runoff.

The behavior of heavy metals (Cd, Cu, Zn, Cr, Pb), nutrients (organic C, P, and N parameters), and major ions were investigated during percolation of roof runoff water through an artificial infiltration site. The concentrations of various components were determined in rainwater, roof runoff, and infiltrating water at various depths in the soil (Mason et al., 1999). Permeable surfaces for roads and footpaths have been used as a means of disposal of stormwater in developed urban areas. Such surfaces provide an alternative to impermeable concrete or tarmacadam surfaces which would otherwise produce rapid stormwater runoff leading to possible flooding and degeneration of receiving water quality through the uncontrolled discharge of polluted urban waters. A further advantage may be obtained from such constructions by undersealing them so as to retain stormwater for reuse for non-potable uses (Pratt, 1999).

Given the characteristics of urban surfaces, and notably the amounts of the different pollutants that stormwater was likely to contain, an experiment was carried out in Valence (France) on two infiltration facilities, in order to assess the impact of intentional stormwater infiltration systems on the soil, and on groundwater. Stormwater from impervious urban areas can adversely impact water quality and quantity. The PET was a control device designed to moderate both the quality and quantity of urban runoff (Li et al., 1999). Urban stormwater often contains high levels of traffic-generated metal elements and particulates. These constituents were transported by stormwater runoff to surficial soils, drainage systems and receiving waters; Sansalone (1999) summarized the in-situ field-scale performance of a passive treatment system called a PET for source control of these constituents. Two infiltration trenches were constructed in a densely built-up area in central Copenhagen and equipped with on-line sensors measuring rain, runoff flow from the connected surfaces and water

level in the trenches. Warnaars et al. (1999) described the field site, the measuring system and the results from an initial soil survey. There were numerous reasons, such as the saturation of the existing downstream sewer system or its concentrate discharge impact on the receiving water, for using stormwater infiltration systems. However, their feasibility within an urban development project depends on physical soil characteristics and contamination risk, and also on socio-economic considerations (Alfakih et al., 1999).

Sediment transport was studied in non-submerged overland flow over grass in a laboratory. Artificial turf (astro-turf) was used to simulate natural grass and no infiltration was allowed at this stage of the investigation. Experiments were conducted for different grass densities, flow rates, sediment inflows, and sediment types (Delectic 1999).

Utilization of parking lots around Hattiesburg, Mississippi was examined to suggest mechanisms for reducing runoff into local streams (Albanese and Matlack, 1999). Suarman et al. (1999) reported a laboratory simulation study, supplemented with information from field installations, in which four paving sub-structures were subjected to sediment loads equivalent to those which could be expected below porous car park surfaces in stable, fully-developed residential neighborhoods in Adelaide, South Australia. Brough (1999) outlined the development philosophy behind the use of ground soakage (construction of soil adsorption basins), and discusses the procedures that have been used in the design of the basins at residential, industrial sites.

Peak flow reduction and aquifer recharge. Infiltration devices were installed in existing housing areas as a means of reducing the peak flow in a combined sewer system. The resulting economic benefits of the retrofit, especially as compared to the installation of a new sewer, were discussed by Simon and Terfuchte (1999). Watts et al. (1999) reported on the utilization of infiltration and groundwater recharge as part of an overall management strategy for Christchurch, New Zealand's waterways and wetlands. The infiltration devices used in the Upper Heathcote catchment included a separate infiltration system for roof drainage, grass swales for non-roof stormwater runoff, infiltration basins and storage of excess runoff for later infiltration. Flood control was also suggested as another benefit of planned infiltration. Yura et al. (1999) demonstrated the effects of a well-maintained infiltration facility on the volume of stormwater runoff from a large-scale housing site. In addition to flood control, the infiltration basin also had other positive effects: groundwater recharge, emergency water storage, and the control of pollutants in stormwater. Oka and Nakamura (1999) used a kinematic wave model in combination with GIS data to demonstrate basin scale effects of storm and infiltration on flood control. Rauch et al. (1999) evaluated an integrated drainage system and simple deterministic models for modeling this system in an Alpine area. The results revealed that the simple models worked well for simulating the system over a long period of time, and that infiltration was recommended, especially when compared to conventional detention ponds. Nawang et al. (1999) compared 1-D nonlinear PDE model results for water level profiles, outflow and stormwater profiles with laboratory investigations. The results were used to develop infiltration design practices for tropical conditions, specifically for Malaysia.

Investigations by van der Werf et al. (1999) in Adelaide, South Australia, demonstrated that infiltration of roof runoff could occur through clay soils overlying a shallow sandstone bedrock even when the cumulative rainfall was significantly greater than the average annual rainfall. Barros et al. (1999) tested the same premise under laboratory conditions using laboratory columns with a shallow bedrock base, an intermediate soil layer (sandy loam and a silty clay loam) and a stone cover layer. The infiltration capacity of the soil layer was found to control the fraction of rainfall that becomes surface runoff. Pitt et al. (1999) investigated the effects of soil type, antecedent moisture content, and soil compaction on the infiltration rates of water. Compaction had the greatest effect on infiltration through sandy soils, while moisture content and compaction affected infiltration through clayey soils. Age since development tests showed that some infiltration capacity could be recovered over time even in severely compacted soils. King et al. (1999), using the Soil and Water Assessment Tool (SWAT) model, compared the Green-Ampt Mein-Larson (GAML) method with the SCS daily curve number (CN) for their abilities to predict runoff volume from the Goodwin Creek watershed. For this large watershed, the curve number method generally underpredicted surface runoff volumes, while no pattern of over- or under prediction was seen with the GAML method. Yu's (1999) comparison of the Green-Ampt model and a spatially variable infiltration model showed that the Green-Ampt model consistently underestimated the infiltration rate when the rainfall intensity was high. The measured rainfall and runoff rates showed a positive relationship between intensity and infiltration rate, indicating a spatial variability in the infiltration capacity and making the spatially variable model a better predictor of infiltration rates.

Infiltration installations for pollutant removal. Pagotto et al. (1999) reviewed the information currently available regarding the ability of infiltration systems to remove pollutants from water, and including the various physical, chemical,

biological and microbiological processes that occur in the unsaturated and saturated zones of the soil profile. Barraud et al. (1999) investigated the impacts on the soil and groundwater of two infiltration facilities, a new cylindrical soakaway and a thirty-year old rectangular chamber, used for treating urban stormwater runoff on the soil and groundwater in Valence, France. The study addressed the impacts of the pollutants contained in the runoff on the performance of these infiltration facilities as well as on the groundwater. A similar study on highway runoff was performed in Germany by Dierkes and Geiger (1999). They tested soil profiles and collected water samples at different soil depths for lead, zinc, copper, cadmium and PAH and found that the highest concentrations were found in the top 5 cm of soil and within two meters of the street.

Dupre et al. (1999) used ultrafiltration at different pHs to investigate the affinity of certain metal ions to form humate complexes in natural waters with a high dissolved organic carbon concentration. The log K constants for sorption to organic colloids (metal-humate complexes) were as follows: Al, Ga, Fe, Th, U, Y, Re (more than 7) >> Cr (5.5) >> Co (3) > Rb, Ba, Sr, Mn, Mg (approximately 2). The tendency of these metals to bind to organic colloids in water should be similar to their ability to bind to organic soils in the vadose zone during infiltration or to organic filtration media in a stormwater filter. Pitt et al. (1999) described adding compost to the natural soil in an infiltration system to improve both the flow and pollutant removal characteristics of the system. When compared to a natural soil infiltration area, the compost-amended soil system significantly increased the removal of both the quantity of surface runoff and the concentrations of many toxicants typically found in urban runoff. The drawback to the compost amendments was the increased nutrient loads in the system effluent. King and Balogh (1999) modeled the runoff losses of nitrates and pesticides from a golf course turfgrass using four irrigation schemes: normal and reduced water application using potable water and normal and reduced water application using reclaimed water. They showed that nitrate losses were significantly affected by the reduction in irrigation water volume, although the pesticides losses were not significant between irrigation strategies. Sansalone (1999) proposed using an oxide-coated sand in a PET to treat urban runoff. Sansalone and Hird (1999) investigated the one-year performance of the partial exfiltration reactor (PER) in removing heavy metals from highway runoff. The tested prototype was able to infiltrate 10 to 30% of the highway runoff while removing at least 75% of the heavy metal load from the stormwater. Hebrard and Delolme (1999) demonstrated that a biofilm of *Pseudomonas putida* on sand could significantly enhance zinc removal from runoff percolating through the vadose zone when the influent concentration ranged from 2 – 20 ppm.

The reservoir structure technique (used in streets and parking lots for infiltration) has been developed in Fr. and is used in Bordeaux to reduce flooding risks and to protect receiving water (Raimbault, 1998). The first function enables the construction of the structure to withstand various types of loads and the second temporarily retains rain, thereby reducing runoff and improving the quality of discharged water. The urban community of Lyons, Fr. uses infiltration facilities for urban drainage. Chocat et al. (1998) presented information on the rehabilitation of old infiltration pits and a study of an infiltration basin. 'Ruwenbos', a small housing estate in the western part of the city of Enschede in the eastern part of Neth., bounded by the German border, was the first project in Neth. where stormwater infiltration was applied on a large scale (Bruins, 1998). Stormwater of all the roofs and most of the streets is transported overland to wadis ('Wadi' is the Arabic word for dry riverbed) where it percolates through the soil. A case history described how stormwater management is carried out in Hillerød, Den. (Sulsbrück et al., 1998). The existing sewer system was enlarged with retention basins and detention ponds and urban storm infiltration has been expanded. The sizing and dimensions for the disconnection of sewered impervious areas to reduce the overflow frequency and hydraulic load of both combined and improved separate sewer systems was explained. The effect of a discharge drain at the bottom of a percolation trench was also investigated and it appeared that, compared to a facility without a drain, the required dimensions of a facility with a drain decrease significantly. (Leefflang et al., 1998).

Infiltrating stormwater locally into the ground instead of discharging to conventional sewers has been used increasingly as a means of controlling urban-stormwater runoff; however, much research is still required, including development of methodologies for determining the design parameters based on local conditions, technologies for soil-clogging prevention, and a simplistic model for assessing the impact on soil and groundwater in local areas (Mikkelsen *et al.*, 1997).

Oka (1996) examined a gravel-storage infiltration method to control urban storm runoff. The gravel layer was inserted in the underground that had been covered with impervious faces, such as buildings and pavements. This method was shown to be more effective for decreasing flood discharges in the urbanized areas than the pipe infiltration method.

Design and maintenance guidelines. Hamacher and Haubmann (1999) compared infiltration as part of a decentral

stormwater discharge program to the more traditional method of rapid removal of stormwater from an area through a planned drainage system. They provided information in the article about stormwater disposal through infiltration, including construction, maintenance and system costs. In Stockholm, infiltration was included as part of an overall stormwater drainage plan. Bennerstedt (1999) reported on the Stockholm plans, including the financing of the stormwater drainage system. Hasegawa et al. (1999) described the data collected during the installation of infiltration systems in Japan and that collected by seven governmental entities on the performance of existing infiltration systems. They also proposed a qualitative method for evaluating the applicability of infiltration for flood control and environmental protection. Argue (1999) described many of the misconceptions about stormwater infiltration systems and proposed design limits and practical advice for dealing with these concerns. Noki et al. (1999) outline some of the current research on infiltration and their application to establishing proper maintenance procedures.

Alfakih et al. (1999) described how siting of infiltration facilities was dependent on physical soil characteristics, groundwater contamination risk, and socio-economic considerations. Their paper provided an overview of feasibility and design criteria for infiltration systems, including a review of currently available models and approaches. Zimmer et al. (1999) argued for the use of physically based models to design infiltration systems, rather than the traditional approach of using a design storm to calculate the required storage volume. They developed diagrams which allowed the designer to read the necessary storage volume for the infiltration system once the soil's hydraulic conductivity was known. Gautier et al. (1999) reported on the progressive clogging of three infiltration facilities and used the results to develop a model for predicting the effect of clogging on the hydraulic behavior and pollutant removal ability of the basins. Todorovic et al. (1999) also evaluated the impact of clogging on the hydraulic performance of infiltration basins over time. They successfully tested their methodology for sizing an infiltration trench/soakaway for the Miljakovac catchment in Belgrade. Laboratory testing using a simulated colloidal suspension was performed by Raimbault et al. (1999) and showed that clogging began with the application of only a small amount of clay. The wetting-drying cycle typically seen in infiltration basins increased the amount of clay retained in the upper layers of a soil and decreased its hydraulic conductivity.

Porous pavement.

James and James (2000) advocated the use of permeable pavement to reduce the impacts of the thermal pollution of receiving waters associated with urban stormwater runoff. They discuss the required design criteria for an acceptable permeable pavement, including long-term performance. Laboratory studies indicated that infiltrating pavements reduced both the flow and contaminant load of runoff to the greatest degree, although asphalt provided the least buffering capacity for acid rainwater and also the least contaminant removal.

Conventional asphalt and porous asphalt were investigated by Pagotto et al. (2000) for their impacts on both runoff quantity and quality. It was found that, compared to the conventional asphalt, porous asphalt attenuated peak flow and mitigated splashing. The porous pavement also retained particulate pollutants by acting as a filter.

According to Anderson et al. (1999), permeable pavements and similar stormwater control devices have not been exploited in the United Kingdom, in part because their adoption has been hindered by a lack of detailed knowledge of their hydrological performance. A range of simulated rainfalls, which varied in intensity and duration, was applied to the permeable model car park surfaces and monitored over an 18-month period. Results demonstrated that evaporation, drainage and retention in the structures were strongly influenced by the particle size distribution of the bedding material and by water retention in the surface blocks.

In order to develop design guidelines for using permeable pavements in parking lots, Andersen et al. (1999) investigated the pavement's hydrological/hydraulic behavior and its impact on evaporation and drainage during a range of simulated rain events and interevent periods. They determined that, for a one-hour, 15-mm simulated rainfall, an initially dry pavement could contain and infiltrate approximately 55% of the water, while an initially wet structure could retain approximately 30%. The ability to infiltrate significant quantities of runoff, especially as compared to asphalt, was confirmed by Booth and Leavitt (1999) in an experimental facility. Pratt (1999) reviewed existing information on water quantity and quality below porous pavement structures and suggested collecting the water that infiltrates through porous pavement structures for use in non-potable applications such as flushing toilets. The reuse of infiltration water below a porous pavement structure was applied at a Youth Hostel in the United Kingdom and details of the design were provided in the article.

Bond et al. (1999) reported on a 13-year study of permeable pavements in the United Kingdom. They found that

microbial degradation of pollutants occurred in the pavement and that the addition of nutrients every three years was sufficient to support the microbial population. The retention ability of a 50-year old porous pavement structure and the soil below was investigated by Legret et al. (1999) and was modeled by LEACHM. Lead, copper, and zinc were not found in significant quantities in the soil below the pavement, i.e., surface retention of those metals, while cadmium was found to have migrated to a depth of 30 cm below the pavement.

Porous pavement was found to reduce storm-runoff-pollutant loadings significantly by Legret *et al.* (1996) at an experimental site that monitored about 30-rainfall events over four years. Influent-pollutant concentrations of SS were reduced by 64% and 79% for Pb.

Detention/Retention Ponds

A variety of pond-like BMPs are used to treat urban runoff, including permanently-filled ponds (wet ponds or retention basins) and ponds that are allowed to go dry between storms (dry ponds or detention basins). Detention basins may be lined or unlined, with unlined ponds usually being vegetated. Bhattarai and Griffin (2000) studied the pollutant removal performance of a concrete-lined detention basin that receives runoff from a highway bridge in Louisiana. The basin primarily acted as a settling basin and was most effective in terms of TSS removal. For other constituents, the basin exhibited a somewhat erratic range of removal efficiencies, but it was still able to reduce their concentrations in most cases. Davies and Bavor (2000) compared the performances of a constructed wetland and a water pollution control pond in terms of their abilities to reduce stormwater bacterial loads to recreational waters. Bacterial removal was significantly less effective in the water pollution control pond than in the constructed wetland, likely because of the inability of the pond system to retain the fine clay particles ($< 2 \mu\text{m}$) to which the bacteria were predominantly adsorbed. The key to greater bacterial longevity in the pond sediments appeared to be the adsorption of bacteria to fine particles, which protected them from predators. Guo et al. (2000) experimented with modifications to the outlet structure of a dry detention basin to improve pollutant removal performance of the pond., and found no conclusive correlation between the pollutant removal efficiency and the detention time. Instead, pollutant removal efficiency in the field was strongly dependent on the inflow concentration.

Heitz et al. (2000) examined the precipitation and runoff patterns on Guam in order to: (1) characterize the hourly rainfall events for volume, frequency, duration, and time between storm events; (2) evaluate rainfall-runoff characteristics with respect to capture volume needed for water quality treatment; and (3) prepare criteria for sizing and designing of storm water quality management facilities. The resulting design curves should lead to a reduction of non-point source pollution to Guam's receiving waters. Marsalek et al. (2000) examined the hydrodynamics of a frozen in-stream stormwater management pond located in Kingston, Ontario, Canada. Measurements of the velocity field under the ice cover agreed well with that simulated by a CFD model (PHOENICS(TM)). During a snowmelt event, the near-bottom velocities reached up to 0.05 m-s^{-1} , but were not sufficient to scour the bottom sediment. Van Buren et al. (2000b) studied the thermal balance of an on-stream stormwater pond in Kingston, Ontario, Canada. During dry-weather periods, pond temperature increased as a result of solar heating, and thermal energy input exceeded output. Conversely, during wet-weather periods, pond temperature decreased as a result of limited solar radiation and replacement of warm pond water by cool inflow water from the upstream catchment, and thermal energy output exceeded input.

Newman et al. (2000b) described the application of the Storage-Treatment (S-T) Block of the EPA Storm Water Management Model (SWMM) to design and/or analyze extended-detention ponds (EDPs). The importance of this refined method for EDP design was emphasized with examples of how the use of rules-of-thumb or BMP-manual guidelines could result in unexpectedly poor EDP performance. Proctor et al. (2000) reported on Kentucky's Sanitation District No. 1 working with a local elementary school to convert a badly eroding stormwater detention basin into an outdoor learning center for the school. The results were that the sewer district gained a corrected detention basin, the public gained an education in stormwater management, the students learned about water pollution, and the school gained an educational resource in the Outdoor Learning Center. Dewey et al. (2000) adapted a two-dimensional, vertically averaged hydrodynamic model to compute the circulation and sedimentation patterns in stormwater detention ponds or other water impoundment facilities. The Circulation and Water Quality Model (CWQM) identified areas in the pond where short-circuiting and dead zones occurred. Sedimentation, based on first-order decay, also could be predicted. Field testing verified that the predicted suspended solids (SS) concentration at the outlet and monitored outlet concentrations agreed.

The question has been raised as to whether stormwater ponds adequately protect downstream aquatic systems from the deleterious effects of stormwater runoff. Lieb and Carline (2000) examined the impact of runoff from a stormwater detention pond on the macroinvertebrate community in a small headwater stream downstream of the pond in central

Pennsylvania, USA. Invertebrate communities 98 m and 351 m downstream of the pond were highly degraded, while a community 798 m downstream was markedly less degraded. Despite downstream improvement, all three sites were considered impaired relative to a reference community. These results were found to generally be in agreement with those of similar studies in other states and reinforced the need for land-use planning that considers the potential negative effects of urbanization on headwater streams. Based on an investigation into phytoplankton and periphyton algal communities of two recently constructed stormwater management ponds, Olding (2000) ponds suggested that stormwater impacts on biological communities are reduced during passage through the ponds, providing a degree of protection for biological communities in receiving waters by reducing harmful toxins and nutrients. The taxonomic composition of the two sites provided an indication of the incoming stormwater quality. The lack of blue-green algae suggested that stormwater facilities may be engineered to inhibit undesirable algal communities. Turtle (2000) studied the impacts of road runoff on spotted salamanders breeding in roadside and woodland vernal pools in southeastern New Hampshire and found that Salamander embryonic survival was lower in roadside pools that received road deicing salt runoff.

Current stormwater quality control pond design in Ontario, Canada typically includes the specification of a uniform detention time for extended detention ponds to ensure water quality control. In reality, the pollution-control performance of such facilities was governed by two opposing forces: improved pollutant removal efficiency over longer detention times and the decreased volume of runoff captured and treated by the facility for longer detention times (Papa et al., 1999).

Three seasonal surveys of suspended solids were carried out in an on-stream stormwater management pond, by means of a submersible laser particle size analyser. Size distributions were measured at up to 17 points in the pond, and water samples collected at the same locations were analysed for primary particles aggregated in flocs. Using a relationship defining the flee density as a function of flee size and Stokes' equation for settling, an empirical relationship expressing the free fall velocity as a function of floc size was produced (Krishnappan et al., 1999). Jacopin et al. (1999) examined the new operational management practices for detention tanks, with grassed banks and bottom installed on a separate stormwater network, during rainfall events in order to limit flooding risk and, at the same time, to reduce pollutant discharges by optimising the settling process.

Use of stormwater retention and detention basins has become a popular method for managing urban and suburban stormwater runoff. Infiltration of stormwater through these basins, however, may increase the risk to ground-water quality, especially in areas like the Coastal Plain of southern New Jersey, where the soil was sandy and the water table shallow, and contaminants may not have a chance to degrade or sorb onto soil particles before reaching the saturated zone. Ground water from monitoring wells installed in basins in Camden and Gloucester Counties, New Jersey, was sampled and analyzed for volatile organic compounds (VOC), pesticides, nutrients, and major ions (Fischer, 1999). Crunkilton and Kron (1999) measured the toxicity of stormwater runoff before and after it had been allowed to flow through a pilot-scale wet-detention basin. Selected heavy metals and PAH compounds were measured in incoming and outgoing-settling basin water. *Daphnia magna* and *Pimephales promelas* (fathead minnow) were exposed to pre and post-settling basin treated stormwater runoff for three test periods of 14 days each in 1996 and 1997.

Stormwater reuse has been incorporated into the design of wet-detention systems constructed in Florida. Stormwater reuse reduces the volume of stormwater discharged downstream thereby decreasing the loss of potentially valuable freshwater resource. Additionally, by reusing the detained stormwater instead of discharging it, the treatment efficiency of the stormwater detention pond was increased thereby decreasing the pollutant load delivered downstream (Livingston, 1999). The suitability of treatment ponds for mitigation of chemical contaminant loads and toxicity was investigated under baseflow conditions in two systems serving urban and industrial catchments (Hickey, 1999).

Approximately 40×10^6 L (10 MG) of stormwater were managed at a hazardous spill site for the release of ethyl acetate (Buckles and Sanborn, 1998). Five earthen dams were constructed in series along a stormwater drainage ditch to contain the contaminated stormwater and were removed after the completion of the project.

Vignoles and Herremans (1996) studied pollutant loads (SS, COD, TKN [total Kjeldahl nitrogen]) in runoff waters from a highway to determine capacity of a settling tank for collecting adequate volume of runoff to mitigate the spread of pollutants.

Solids-settling characteristics of urban storm runoff have been addressed by Pisano (1996), due to their importance in designing CSO and stormwater high-rate treatment facilities. Solids settling curves and median settling velocities for

different waste types have been presented. Settling column methods and solids settling curves for various wastes were presented by Pisano and Brombach (1996) along with global estimates of median settling velocities and results of recent German research.

Multiple drainage objectives and pond design conflicts.

Wada et al. (1999) investigated the possibility of using a storage tank or pond, for both flood control and stormwater control. They found that the first flush could be directed into an initial storage area, while peak runoff flows could be directed to a secondary storage area. The suitable storage volume of the first pond would be 1-2 mm of runoff and the secondary pond volume would be 3-4 mm of runoff. Cabot et al. (1999) also described the dual use of ponds in Barcelona, Spain, where several detention facilities have been designed to simultaneously address both flooding and CSO. The design procedure has been validated with a detailed model, and a simplified rule has been developed stressing the use of the 10-year design storm. The 100-year design storm was then used to obtain the design capacity of the overflow structures of the facilities. Drainage objectives in Belgrade, Yugoslavia were to separate stormwater from wastewater in areas of existing combined systems and to limit peak discharges by means of detention ponds in the upstream part of the drainage areas for downstream flood prevention (Despotovic et al., 1999).

Henderson (1997), Sela and Chidananda (1997), Yeh and Labadie (1997), and Smith and Sila (1997) reported that stormwater-detention basins (ponds) in urbanized areas have been designed for many purposes, including flood and pollution control and recreation.

Gupta and Saul (1996) discussed use of storage tanks incorporated into the design of combined sewer systems at two sites in northwestern England for controlling discharges to receiving waters. The Regional Municipality of Hamilton-Wentworth operates a large combined-sewer system with 20 overflow structures that result in an average of 23 overflow events per year per outfall. Stirrup (1996) concluded that the only reasonable means of dealing with large volumes of CSO in Hamilton was to intercept it at the outfalls, detain it, and convey it to the wastewater treatment plant after the storm event ends. Target reductions of CSO to be achieved are 1 to 4 per year on the average.

Nix and Durrans (1996) analyzed offline-detention systems as a means of stormwater management and concluded that offline systems required considerably less storage than inline systems to achieve the same management goal.

Pond sizing.

Guo (1999) described a simple method to size stormwater detention basins using a volume-based method such as provided by the Federal Aviation Administration that was applicable to small urban catchments. The average outflow from the detention basin (the most important aspect affecting reliability) was found to be related to the time of concentration of the catchment and the duration of the design storm. Guo and Adams (1999a) described how the flow-capture efficiency and average detention time (the performance measures commonly used in assessing the long-term pollutant removal effectiveness of stormwater detention ponds) can be statistically estimated. Guo and Adams (1999b) further described the analytical probabilistic approach that can be used for evaluating designs of detention facilities that was a computationally efficient alternative to continuous simulation. Papa et al. (1999) described how the pollution-prevention performance of detention facilities was governed by two opposing forces: improved pollutant-removal efficiency over longer detention times, and the decreased volume of runoff captured and treated by the facility for longer detention times. The combination of these effects produces a maximum attainable level of long-term pollution-control performance at an optimal detention time. Harston and Joliffe (1999) described the recent New South Wales (Australia) stormwater management manual which has identified three different classifications for sediment basins. Type F and Type D basins were designed for total containment of runoff and discharge after a predetermined time period to allow efficient containment and release after flocculation to settle the fine sediments.

Retention basins should be cost-effectively sized based on analysis of local-hydrological characteristics and their impact on stormwater-runoff capture. Urbonas *et al.* (1996) suggested that fine-tuning to site characteristics and local conditions can save significant costs over recommending oversized ponds. Guo and Urbonas (1996) presented a strategy for estimating stormwater-detention volume to achieve quality control based on the fraction of storm runoff volume captured and the number of storm runoff events predicted to occur in a given time period.

Kachalsky *et al.* (1996), discussed an approach to optimal sizing of a CSO-retention facility that was used for a planned CSO facility in Jamaica Bay, New York, NY, by the New York City Department of Environmental Protection. In this approach, an evaluation of the impact to water quality improvement versus construction cost of the CSO-retention facility

was considered. Kluck (1996) investigated performance of CSO-settling tanks for certain selected designs as result of time-varying flowrates and dimensional effects as well. This research evaluated the effectiveness of baffles and diffusers and confirmed the importance of the shape of the tanks.

Locating detention facilities in older areas.

Rivard and Dupuis (1999) described how older drainage systems, especially combined sewers, that frequently experience hydraulic surcharges can sometimes be improved by restricting the inflows at the inlets, causing a limited retention of stormwater on the streets. Scott et al. (1999) examined both onsite detention and on-site retention for a set of hypothetical urban catchments ranging in size from 14 ha to 210 ha. The objective was to achieve the same peak flow rate reduction at least cost. The onsite retention facilities was shown to out-perform the detention in most of the medium to large catchments.

Modeling pond performance.

Hollingworth et al. (1999) also presented an analytical probabilistic model (MTOPOND) that used probability distribution functions of rainfall characteristics in order to develop closed form expressions for the long term pollutant removal efficiency of stormwater ponds. Operational management practices for detention facilities to limit flooding risks simultaneously with reduced pollutant discharges was possible by optimizing the settling process, as described by Jacopin et al. (1999a). They found that proper descriptions of the particle sizes were critical and that the particle size distribution in the surface sediments were close to those of the suspended solids in the stormwater. Jacopin et al. (1999b) further described the optimization process where the detention facilities were empty most of the time, offering a large safety margin to protect against flooding. The detention facilities store all of the runoff from light and medium rainfall events, consuming about half of the detention capacity. The probability of exceeding the tank capacity was small, even for the larger storms. Adamsson et al. (1999) found that computational fluid dynamics (CFD) was a good tool for studying the hydraulic properties of detention basins in urban drainage systems.

According to Greb and Bannerman (1997), the influent particle-size distribution affected the efficiency of an urban residential area stormwater wet pond's performance on sediment and associated pollutant removal. Karounarenier and Sparling (1997) studied toxicity of stormwater-treatment-pond sediments. Guo (1997) measured the amount of heavy-metal content, organic content, and mass distribution of the bottom sediment in an 18-year-old-single-purpose-dry-stormwater-detention basin, assessed the effect of sedimentation on flood-control capacity, and determined values for predicting amounts of sediment and heavy-metal accumulation. Results of dye-tracing studies performed in a stormwater pond in Kingston Township, Ont., Can. demonstrated an increase in retention times with reduction in the velocity and volume of short-circuiting flow and a decrease in wind-generated-flow patterns due to the installation of retrofitted baffles (Matthews et al., 1997).

Yeh and Labadie (1997) applied successive-reaching-dynamic programming (SRDP) and a multiobjective-genetic algorithm (MOGA) to the design of a stormwater-detention-system in the Pazam watershed located in southern Taiwan. This study indicated the computational efficiency of the SRDP algorithm and the MOGA's nondominated solutions for trade-off analysis. Lawrence et al. (1997) reported on the considerations involved in stormwater-hydrological and pollutant-mobilization processes and the selection of stormwater-detention and pollution control BMP. A summary of the major structural and nonstructural BMP commonly used including pollutant removal and flow attenuation capacities of each BMP was provided.

Observed pond performance.

Pettersson et al. (1999) studied the pollutant-removal efficiency of two stormwater ponds in Sweden. Observed outflow pollutant conditions were independent of the influent conditions for the two ponds. They also found that pollutant removal efficiency increased for increasing values of ratio of the pond surface area to the watershed impervious area, up to about 250 m²/ha, while the benefits of larger ponds were not as important. Bartone and Uchirin (1999) compared the performance of two dry-stormwater-detention facilities, one having a concrete low-flow channel, and the other with a vegetated low-flow channel during four events. As they expected, the detention pond having the concrete channel was ineffective for stormwater quality control. However, the basin with the vegetated channel was also found essentially ineffective for water quality improvement, with flushing of previously captured pollutants being the most likely reason for the poor performance. The retention of heavy metals in a wet reed-bed wetland were compared to retention in a dry-detention pond near London, United Kingdom, by Hares and Ward (1999). A higher percentage removal occurred in the monitored wetland facility than in the dry pond. Shatwell and Corderly (1999) examined nutrient removals in a pond in Sydney's (Australia) Centennial Park that receives stormwater from a 120 ha catchment that was predominantly

residential. They found significant amounts of phosphorus and sediment accumulating in the pond, especially during the small- to medium-sized rain events (approximately 60% phosphorous and 80% suspended sediment reductions).

Krishnappan et al. (1999) monitored in-pond particle sizes using a submersible laser particle size analyzer, reducing potential changes in particle characteristics that may occur during sampling. The suspended solids were mostly composed of flocs, and were about 30 μm in size during winter surveys and about 210 μm during the summer surveys. MacDonald et al. (1999) investigated the removal of heavy metals in a detention pond in Scotland. They found that the sediment in the pond may reach unacceptable concentrations of heavy metals within twenty years. Petterson (1999) examined the partitioning of heavy metals in particulate-bound and dissolved phases in a stormwater pond in Goteborg, Sweden. The results showed a clear variation in lead partitioning affected by specific conductivity.

A monitoring study in Kingston, Ont., Can. (Shaw *et al.*, 1997) concluded that regardless of the magnitude of inflow, the length to width ratio (3:2) of the urban-stormwater-detention pond studied and inflow momentum promote short-circuiting of the flow and limit settling efficiency.

Maxted and Shaver (1966) studied the use of retention basins, constructed as the best management practices (BMPs) to mitigate stormwater impacts on aquatic life. Physical habitat and biological measurements were taken below eight stormwater basins (BMPs). Two of the sites were in commercial land use, while six were in residential areas. The results were compared to 38 sites with no BMPs that had been sampled in 1993. The BMPs did not prevent the almost complete loss of sensitive species. The BMPs did not attenuate the impacts of urbanization once the watershed reached 20% impervious cover. This study showed that the data set size used here was too small for a conclusive evaluation of the effectiveness of stormwater controls to protect stream biota and habitat. It is also possible that the stormwater facilities studied were not used long enough to achieve improvements in habitat and to repopulate the species.

Papa and Adams (1996) analyzed the implications of required detention times for retention basins with respect to their actual pollution control performance. It was found that pollution-control performance is maximized with typically short-detention times and diminishes monotonically with additional detention time thereafter.

Van Buren *et al.* (1996) assessed the pollution-control performance of a retention pond in Kingston, ON, Canada, and provided results on removal rates for SS, nutrients, metals, organic contaminants, and selected dissolved constituents. Internal pond baffles were evaluated, and it was found that extended hydraulic-residence times and prevention of flow short-circuiting result in increased particulate settling and associated contaminant removal. Stanley (1996) quantified removal efficiencies achieved by a retention pond in Greenville, NC for SS, N, P, TOC (total organic carbon), and selected metals. The benefit of constructed reed beds in treating stormwater overflows was evaluated by Green and Martin (1996) in terms of reductions in discharges of BOD₅, SS, NH₄⁺, and TON (total organic nitrogen).

Problems observed with stormwater ponds.

Beyerlin (1999) described the short-comings of relying on stormwater-detention facilities for complete mitigation of urban runoff problems. Increased winter flood flows, decreased summer low flows, and a general degradation of the stream systems has occurred with development. It was concluded that these problems persisted because of the attempt of replacing the complex interactions of the hydrologic cycle with a pond, which was not possible. Brown et al. (1999) described the degradation in quality in Sydney (Australia) Centennial Park's ponds over the past 150 years. Pond rehabilitation techniques have been developed and were being implemented, based on wetland principles.

Wetlands

Constructed wetlands have been used to capture, detain, and treat stormwater runoff from urban areas because they have the potential to treat a variety of pollutants. Knight and Kadlec (2000) presented an overview of constructed wetlands used for water pollution control. Bachand and Horne (2000) examined the effect of vegetation type on nitrogen removal rate in wetlands used to treat wastewater, including urban runoff. Based on the study and a literature review, in organic carbon-limited free-surface wetlands, a mixture of labile (submergent, floating) and more recalcitrant (emergent, grasses) vegetation would be recommended for improving denitrification rates. Carleton et al. (2000) examined the pollutant removal performance of constructed wetlands treating stormwater runoff from a residential townhome complex in northern Virginia. Median load removals of all constituents were greater for a subset of storms that had inflow volumes less than the maximum volume of the marsh. Estimated removals were positive for most constituents and consistent with expectations based on the relative ratios of wetland area to drainage area at the two sites. Zhu and Ehrenfeld (2000) compared the ability of sediments from Atlantic cedar wetlands in suburban and undisturbed watersheds to remove added

inorganic N in laboratory incubations. Results suggested that wetlands in suburban drainages may have limited ability to retain frequent, pulsed N inputs from runoff, and high intrinsic N mineralization in N-saturated sediments can become a cause of water quality degradation. Graham and Lei (2000) evaluated the effective long-term operation of stormwater management ponds/wetlands, including removal, methods of removal and disposal of removed sediments.

Davies and Bavor (2000) compared the performances of a constructed wetland and a water pollution control pond in terms of their abilities to reduce stormwater bacterial loads to recreational waters. Bacterial removal was significantly less effective in the water pollution control pond than in the constructed wetland. Quintero-Betancourt and Rose (2000) assessed the microbial quality of stormwater and/or reclaimed water in terms of bacterial indicators, coliphages, *Cryptosporidium* and *Giardia* in order to determine its suitability for use in recharging stressed wetlands overlying a public water supply wellfield. Preliminary data demonstrated that the level of bacterial indicators such as fecal coliforms and total coliforms in three of the lakes sampled were above the water quality standard established by the Florida Department of Environmental Protection for ambient waters, and other pathogens and indicators were detected.

Wetlands have been chosen for retrofitting existing developments or stormwater detention facilities to improve the treatment of stormwater pollutants. Kerr-Upal et al. (2000) presented a conceptual plan to retrofit a wetland component within the a stormwater management facility in Toronto, Canada, using three wetland design options. Traver (2000) converted an existing stormwater detention pond to an extended detention wetland at a site near Philadelphia, Pennsylvania. The project maintained the original storm water controls and provided proper hydrologic growth and non-point source pollution control. The City of Elkhart, Indiana has constructed an artificial wetland at a CSO outfall to capture and treat overflows prior to discharge into the Elkhart River. The treatment process consisted of (1) a bar screen/sedimentation basin to remove grit and floatables, (2) nearly 30 different species of native aquatic and transitional vegetation, and (3) a downflow drainage and collection system to enhance biological removal of dissolved organics and inorganics, dissolved metals, and suspended particulates (Umble et al. 2000). Davis et al. (2000) reported laboratory and field results of a study of bioretention for treating urban runoff. Kim et al. (2000) evaluated the capacity of bioretention to remove nitrate from urban runoff using a design modification to incorporate a continuously submerged anoxic zone with an overdrain. Work so far has focused on selecting an electron donor/carbon source that promotes significant denitrification and is stable for an extended time in the subsurface. Further studies will use the electron donor (newspapers, wood chips, small sulfur particles/limestone) with the best nitrate removal efficiency and effluent quality.

Since surface flow constructed wetlands (SFCW) are now often designed with low aspect ratios to circumvent surfacing problems, plug flow is not ensured; therefore, alternative models which more accurately describe the flow must be considered. However, to solve the alternative models, a value for dispersion is required. The fundamental variables affecting dispersion are the interstitial velocity (dependent on flow rate, porosity, and cross-sectional area) and the pore geometry (dependent on media characteristics such as average grain diameter and permeability). The dispersion number also will fluctuate with a series of uncontrollable variables specific to a particular SFCW situation. Cothren and Daly (2000) reported the results of their research to extend the results of an empirical relationship between the interstitial velocity as a function of flow rate and aspect ratio and the dispersion number developed using a bench-scale model to the field scale application. Larm (2000) presented a methodology for quantifying yearly and monthly material transport into and out of stormwater treatment facilities (STFs) and discussed problems related to monitoring and estimation of reduction efficiency. Standard values of runoff coefficients and pollutant concentrations together with precipitation data and estimated areas of different land uses within sub-watersheds were used to predict loadings to a multiple pond-wetland STF. A comparison of standard concentrations with measurements shows good correlation for nitrogen, but variable correlations for other pollutants. Tucker and Acreman (2000) described a user-friendly, physically-based model for the estimation of ditch water levels in wet grassland drainage ditches and thus assess the impacts of different water level management strategies on ecological communities and agricultural practices in wet grassland areas. Simulated rain events and runoff were found to produce a more realistic influent to a stormwater treatment wetland than do averaged inlet flow and concentration. Network flow models provided a more realistic prediction of a treatment wetland's internal flows than did plug flow or complete mixing estimation (Werner and Kadlec 2000). Moustafa (2000) extended empirical mixed-reactor models governing phosphorus (P) retention and nutrient assimilation in lakes and reservoirs to include free surface water wetland treatment systems. It was found that sedimentation rates, loading rates, and settling velocity in these wetlands, and their typology were comparable to their lake counterparts. Stormwater treatment areas (STAs) are extremely large-scale (several square miles) wetland BMPs being constructed on former agricultural areas of south Florida to provide total effective treatment of stormwater before discharge to the water conservation areas and Everglades National Park. Hyder and Hilton (2000) reported on the hydraulic design model that provides a technical basis for management of STAs. Neumeister et al. (2000) presented a modeling approach to evaluate design alternatives for STAs.

The flexibility of their model allowed impacts from alternative design scenarios to be evaluated and incorporated.

Because vegetation is crucial in many wetland treatment processes, the establishment of vegetation in newly constructed wetlands is important. Fassman et al. (2000) examined strategies for planting constructed wetlands to enhance development and survival of constructed wetland systems used for stormwater management and mitigation credit. Galatowitsch et al. (2000) used wetland biomonitoring approaches to determine when changes in response to stressors were occurring and to predict the consequences of proposed land-use changes for 40 wet meadows in Minnesota. Site impacts (stormwater, cultivation) and landscape disturbance (agriculture and urbanization, combined), coincided with a reduction in native graminoid and herbaceous perennial abundance.

One often cited advantage of wetlands for stormwater treatment is the associated development of wildlife habitats. A study by Bishop et al. (2000a) of 15 stormwater pond wetlands and one natural wetland varying in age from 3 to 22 years in the Guelph and the Greater Toronto Area (GTA) in Ontario, Canada, showed that wildlife made use of the ponds, but species richness at almost all sites was low to moderate, indicating that the ponds did not provide high quality habitat for wildlife. Due to concerns that wildlife would be attracted to stormwater detention ponds and be exposed to contaminants accumulating in these ponds, contaminant levels in ponds, sediments, and wildlife were also investigated (Bishop et al. 2000b). A variety of impacts detected in wildlife species including fish, songbirds, and amphibians led the authors to conclude that stormwater ponds did not offer clean ecosystems for wildlife and the monitoring of contamination and its effects within stormwater ponds was necessary. The Lake County Sanitation District has developed a program to recycle treated wastewater in Lake County, California. The plan included constructed wetlands to improve water quality, enhance wildlife habitat, offer evapotranspiration of excess water, and provide public benefits by creating settings for passive recreation and wildlife study. Kimmelshue et al. (2000) presented a paper which included results from a wetlands screening study, a preliminary design effort and the design and construction of an initial wetland.

According to Koob et al. (1999), the successful design of constructed wetlands required a continuous supply of water or vegetation that can withstand drought conditions. Detention structure designs should be based on times between events as well as on hydrologic return periods, since between events was when most evaporation and infiltration losses were likely to occur. Serrano et al. (1999) investigated phosphorus (P) concentrations in Donana seasonal wetlands in southwestern Spain as the wetlands started to fill following storm events after a drought. NPS N from riverine origin was a major water quality problem throughout the world. Hunt et al. (1999) reported that total annual N removal for the in stream wetland was approximately 3 kg/ha per day, which was about 37% of the inflow N. Removal of both $\text{NO}_3\text{-N}$ and total N ($\text{NO}_3\text{-N} + \text{TKN}$) were positively correlated to temperature with r-values of 0.77 and 0.62, respectively. According to Zhu and Ehrenfeld (1999), the presence of urban and suburban lands adjacent to wetlands may cause changes in nutrient-cycling processes, due to changes in the quality of the ground and surface waters that drain from the developed uplands into the wetlands. The alternations in hydrology and the input of mineral-rich sediments, in addition to excess N from the septic drainage and road runoff, can apparently cause increases in N mineralization within the wetland sediments, thus exacerbating the direct deleterious effects of roads and housing on water quality. Quantitative estimates of denitrification were needed in designing artificial wetlands to optimize nitrate (NO_3^-) removal. Acetylene blockage and N-15-tracer methods were employed to quantify denitrification in constructed wetlands receiving agricultural tile drainage, using plastic tubes to enclose in situ mesocosms. Because water infiltration carries NO_3^- through the anaerobic sediment/water interface for denitrification, a subsurface-flow wetland may denitrify more NO_3^- than a surface-flow wetland (Xue et al., 1999).

According to Guardo, (1999) the Everglades Nutrient Removal (ENR) Project, a 1544-ha wetland, was designed and constructed as a pilot project to gain experience on design, construction, and operation of the stormwater treatment areas. For the 732 days analyzed (19 August 1994 through 19 August 1996), the average water inputs into the project were as follows: 86.2% from the inflow pumps, 11.2% from rainfall, and 2.6% as emerging measured and estimated seepage from an adjacent area with higher stages; the average water outputs from the project consisted of 85.1% from the outflow pumps, 8.9% as evapotranspiration, and 6.0% as a net seepage and groundwater component. The ENR Project's purpose was the removing of nutrients (especially phosphorus) from agricultural drainage and stormwater runoff before entering the Everglades. The hydrology and water quality of an urban wetland receiving stormwater runoff from a municipal maintenance garage were measured during the summer of 1993 to evaluate the wetland's water quality enhancement function. According to Thurston (1999), hydrologic and analytical data together suggest that sedimentation was the primary mechanism actively reducing water column concentrations of lead and petroleum hydrocarbons introduced to the wetland via stormwater runoff.

It was evident that existing designs for the control of highway discharges were primarily if not exclusively intended to control runoff volumes rather than as any complementary pollution treatment function. However, regulatory pressures on highway authorities and agencies were increasingly requiring that drainage controls should include reference to water quality treatment and the clear inadequacy of conventional drainage systems has stimulated interest in the design, implementation and operation of alternative vegetative systems, such as swales and wetlands (Ellis, 1999a and 1999b).

To address the unknowns and design concerns of a stormwater wetland system, a bench-scale vegetative-treatment-cell study has been conducted for the purpose of examining nutrient and metal dynamics and removal efficiencies of three individual plant species under various stormwater-pollutant loadings and detention times. The plant species being evaluated are: cattails (*Typha latifolia*), reeds (*Phragmites* sp.), and bulrushes (*Scirpus* sp.) (O'Shea et al., 1999). The design and pollutant removal performance of seven wetland mitigation sites and two detention basins with emergent vegetation in Virginia were examined over a three-year period to assess the effectiveness of mitigated wetlands for the control of NPS pollution and the influence of design on wetland performance as a BMP, in a study sponsored by the Federal Highway Administration and the Virginia Department of Conservation and Recreation (Shaw et al., 1999). The Tollgate District Sewer Separation Project involved the separation of a combined sewer system, and the creation of a wetland detention basin. In addition to its stormwater detention uses, the wetland serves as a wildlife refuge, learning center, and a local point of public outreach to bring the community together (Lindemann, 1999).

The Virginia Stormwater Wetland Simulation Model (VASWETS) was developed on the basis of a double-layer (water column and substratum) box approach to model the fate of pollutant transport in bucket wetlands (Liao et al., 1998a and 1998c) and has the ability to predict and optimize performance and to compare design criteria of stormwater-wetland systems. The Harris County Flood Control District implemented a wetland mitigation bank project northeast of Houston, Tex. that included highway runoff. The project includes 89 ha (220 acres) of stormwater-polishing wetlands as part of the overall 607 ha (1 500 acres) Greens Bayou Wetland Mitigation Bank (Knight and Koros, 1998). The Tollgate Drain project of Ingham County, Miss. created a wetland to act as a natural filtration system for stormwater runoff from a 95 ha (234 acre) developed watershed. At \$6.4 million, the system cost was about half of the other options (Lindemann, 1998). Denison and Tilton (1998) provided a summary of the Rouge Project wetland demonstration including wetland design, construction, and monitoring and assessed the practicality of using wetlands for stormwater treatment. Case studies of the Wetland Conservation Area located in New Albany, Ohio, the Streetsboro Wetland Park in Streetsboro, Ohio, and the Oakland Ravine Wetland Treatment System of the Borough of Queens, N.Y. illustrated that skillfully designed wetland projects represent a tool for communities to show compliance with the upcoming Phase II NPDES regulations (Evans, 1998). The wetlands serve as CSO reduction, stormwater treatment, park enhancement and educational uses. Scholes et al. (1998) presented monitoring and performance results from constructed-wetland treatment systems at two selected sites in southeastern U.K., both of which receive large volumes of urban runoff. The results show widely varied influent pollutant concentrations and removal efficiencies, and indicate that the tissues of reeds in the wetlands accumulate metals. A study of nutrient absorption capacity of different species of Lemnaceae (duckweed) in a stormwater detention pond concluded that monoculture *Lemna minor* consistently removed the largest amount of NH_3 from stormwater and had the largest biomass density while a polyculture of *Lemna minor* and *Spirodela polyrrhiza* was the most stable nutrient sink and removed the largest amount of P from stormwater in eight weeks (Pernial et al., 1998).

Environmental agency effluent quality data were given for 39 sites where reed beds either treated stormwater and secondary effluent together or have been installed as remedial treatment for works struggling to meet secondary treatment standards (Green et al., 1998). Brdjanovic et al. (1998) attributed deterioration of biological P removal (BPR) efficiency observed after heavy rainfall and weekends to excessive aeration. The lull in BPR performance was originally thought to be low plant loading that took place during such events. A quarry in Du Page County, Ill. currently used for temporary flood control storage was evaluated for treatment of stormwater and dry-weather flow in order to improve water quality to Salt Creek (Lampe et al., 1998).

As wetland ecosystems degrade due to human actions, restoration efforts have become more pronounced. Mass-balance models could provide valuable information about ecosystems with respect to input sources and the relative importance of each pollutant load, based on a study of P and SS loadings to Cootes Paradise Marsh in Hamilton Harbour, Lake Ontario, Can. (Prescott and Tsanis, 1997). Shutes et al. (1997a and 1997b) reported on the results of two case studies of the pollution-removal performance of constructed wetlands for urban-stormwater-runoff treatment. The design of constructed wetlands included primary-treatment components, substrate composition, and flowrate regulation. Two subsurface-flow-constructed wetlands were tested for pollutant-removal performance in conjunction with an online-stormwater-detention pond. The wetlands were able to maintain removal of SS (46%), dissolved metals (Cu 50%), and organic C (10%)

(Rochfort *et al.*, 1997). Stormwater-control basins can be easily and inexpensively modified to act as stormwater-treatment wetlands. Preliminary results indicated removal of 93% SS, a total P removal of up to 83%, and a minimal amount (22%) of total N removal (White *et al.*, 1997).

Somes and Wong (1996) modeled a series of hypothetical wetland systems to determine the influence of different outlet types on their hydrologic regimes. It was concluded that the design of constructed wetlands for stormwater-pollution control involves consideration of the inherent variability of storm events and intervening dry periods to size the wetland storage volume and outlet characteristics. The outlet of a wetland must retain the stormwater in the wetland as long as possible but also provide adequate wetland storage capacity for the next storm event. This study concentrated on three outlet configurations for draining wetlands: an orifice, riser, and siphon. Each outlet type was evaluated for its ability to maintain the hydraulic effectiveness and hydrologic regime of the wetland.

Existing wetlands located in the future Rocky Ridge subdivision of Calgary, AB, Canada will be retained and incorporated into an integrated-stormwater-management system for the subdivision. Van Duin *et al.* (1996) discussed measures taken to protect the integrity of these wetlands during and after construction of the subdivision including a multiyear-monitoring program. Werner and Kadlec (1996) evaluated the performance of constructed wetlands in terms of effluent concentrations resulting from impulse-tracer inputs to the systems.

Design guidelines.

Koop *et al.* (1999) stress that the successful design of constructed wetlands requires a continuous supply of water for vegetation to withstand drought conditions. They acknowledge that there were drought tolerant species of vegetation that can be used in constructed wetlands, however, it can take several days to re-establish the attached bacteria communities that were necessary for optimum pollutant removal. Lawrence and Breen (1999) described new design guidelines for constructed wetlands. They also highlighted some areas where further information was required to facilitate a more rigorous analysis of wetlands to optimize their selection, design, and assessment. Lawrence (1999) described a generic pond and wetland model that can provide water quality assessments for a range of geographic areas and information needs.

Persson *et al.* (1999) examined the hydraulic efficiency of constructed wetlands. They found that proper control of the hydrologic regime of the wetland and optimal flow hydrodynamics within the wetland were necessary for their sustainable operation. They concluded that many of the problems encountered in constructed wetlands can be minimized, or avoided, by good engineering design principles, including optimizing their shape and layout. Rash and Liehr (1999) also looked at the flow patterns within a constructed wetland near Wilmington, North Carolina, using lithium chloride tracers. Short-circuiting was common in subsurface-flow wetlands, while vegetated free water surface wetlands were well-mixed and not as subject to short-circuiting.

Wetlands for CSO control.

Liebig, *et al.* (1999) described the stochastic behavior of hydraulic and pollutant loadings of constructed wetlands for CSO and stormwater treatment. A comprehensive three-year monitoring program of a constructed CSO wetland in Kamen-Methler, Northrhine-Westfalia, Germany, was undertaken to monitor the pond's effectiveness and to establish planning, design and operation guidelines. Wong *et al.* (1999) reported on the performance of the Braunebach research wetland in Germany and described the suitability of a two-parameter first-order-decay model for predicting the performance of the constructed wetlands for the treatment of CSO. A total of 30 CSO events were monitored and the results demonstrated the suitability and reliability of this model for SS, BOD₅, total phosphorus and soluble reactive phosphorus. The Fulda Fellenweg wetland system, also in Germany, was built in 1992, and consists of a 550 m² soil filter planted with reeds, and a basin with a detention volume of 786 m³. Born (1999) described the performance of this system in treating CSO. The efficiency of the system was about 90% for COD, NH₄-N, SS and PO₄-P and the removal efficiencies were independent on the residence times in the system. The permeability did not decrease during the five-year monitoring period. The main design parameter for the system was the surface loading rate (usually about 0.011 L/m²-s). Faster rates (up to 0.027 L/m²-s) showed only a negligible decrease in performance.

Observed wetland performance.

Guardo (1999) examined the nutrient removal ability and the hydrologic balance of a wetland located in South Florida over a period of two years. A 1540 ha wetland was constructed as a pilot project as part of a major study investigating methods to reduce nutrient discharges into the Everglades. Hunt *et al.* (1999) studied nitrate removals in a wetland located in North Carolina. The average concentrations were reduced from 6.6 to 2.0 mg/L. Nitrate mass removals were highly

correlated to inflow concentrations in the warmer months when biological processes were more active, while the ammonia mass removals were highly correlated to inflow ammonia concentrations during the cooler months. Moustafa (1999) described monitoring results from Boney Marsh, Florida. Water-loading rate, water depth, phosphorus-loading rate, and water-retention time were examined for their influence on phosphorus removals. A simple quantitative diagram was developed that related these factors to phosphorus removal. White (1999) described the performance of a small wetland, located near Mobile, Alabama, for reducing suspended solids and nutrients in stormwater. The wetland system was constructed in January 1996 and monitoring results have shown that suspended solids and total phosphorus removals were significant (up to 90%), but that nitrogen removals were much less (about 20%).

Bacteria removal rates in a marshland upwelling system were reported by Rusch et al. (1999). Fecal coliform (FC) bacteria analyses indicated reductions from an average influent value of about 1500 FC/100 mL to an average of 2 FC/100 mL in 5-foot deep monitoring wells. A filtration model predicted that the k value for the first order removal reaction was 0.40 – 0.56/d and that the predicted content of FC in the wetland surface was near zero.

Scholes et al. (1999) described the performance of two wetlands located near London, United Kingdom. Removal efficiencies were greater than 65% for Zn, Cd, Pb, and Cu, at one site, while they were only about one-half of these rates at the other site. They also investigated the role of microorganisms in removing the heavy metals and two metal tolerant strains were found to accumulate Pb and Zn. It was believed that this ability may prove to be an important year-round pollutant removal process. Lead and petroleum hydrocarbons (originating from a municipal public works yard) were monitored in an urban wetland by Thurston (1999). Levels of these compounds in the sediments were higher near the inlet than elsewhere. It was concluded that sedimentation was the primary mechanism responsible for reducing the concentrations. Dombeck et al. (1999) examined the assimilation of trace metals in wetland sediments at the Sacramento (California) Regional County Sanitation District's Constructed Wetland Demonstration Project. Six metals (silver, cadmium, copper, mercury, lead and zinc) consistently exceed mass removal rates of 60%. Chromium and nickel were observed in concentrations approaching or exceeding the freshwater sediment Probable Effect Levels (PEL). It was expected that the nickel enters the wetland in a predominantly dissolved and strongly organic-complexed form.

Problems in wetlands.

The aquatic plant community was found to dramatically degrade in an urbanizing wetland study area located in Portland, Oregon, during studies by Magee et al. (1999). They were concerned that current wetland management practices were replacing natural marshes and wet meadow systems with ponds, further resulting in changes in the composition of the plant species assemblages. Revitt et al. (1999) studied the pollutant removal at two constructed wetlands. The behavior of suspended solids was the greatest concern, as higher outlet concentrations were consistently discharged compared to inlet conditions, presumably due to re-suspension.

Russell (1999) was very concerned about artificial wetlands providing suitable habitats for mosquitoes in Australia. The Ross River virus, spread by mosquitoes, was of special concern as it was responsible for thousands of cases annually of a disease that was severely debilitating. It was suggested that mosquito control should not rely solely on chemical and biological agents, but that the design parameters of wetlands can also be important. Shallow water and dense vegetation promote mosquito production, while deeper habitats with cleaner steeper margins, and more open water, produce fewer mosquitoes. Aeration and fountains can reduce larval densities and vegetation thinning can assist mosquito predators.

Critical Source Area Controls

In their paper, Cairo and Pujol (2000) advocated the use of membranes and biofilters for urban wastewater treatment. They demonstrated that the membrane and bio-filters produce a high quality effluent during both dry- and wet-weather flows. Lau et al. (2000) demonstrated that biofilters, even with a biofilm as young as three days, is capable of providing good removal efficiencies for both dissolved and sediment-adsorbed metals. During the nine-week operating of a laboratory-scale biofilter, 90% of the total Cu and Zn were removed. Field-testing of a submerged, aerobic biofilter for the treatment of stormwater runoff was reported by Mothersill et al. (2000). They found that the biofilter removed 97% of the suspended solids in the runoff; however, the suspended solids accumulation interfered with the nutrient removal through bacterial assimilation. Removal efficiencies of 64% for ammonia nitrogen were seen throughout the life of the filter. Backwashing to remove sediment was found not to be sufficient to maintain optimal biological filtration conditions.

Stormwater runoff contains a greater variety of pollutants than sanitary wastewater including such priority pollutants as benzene, PAH, pesticides and toxic heavy metals (Fan et al., 1998). These pollutants are usually associated with particles < 50 μm which are difficult to remove using standard WWF sedimentation technologies, however, advanced

sedimentation systems have shown effectiveness for removing such particles. Biological leaching was proposed as a method to treat urban stormwater sediments contaminated with trace metals. An iron oxidizing bacteria indigenous to the sediment removed soluble Cu (64% solubilization) and Zn (98% solubilization) in laboratory and pilot-scale experiments (Anderson et al., 1998). Lainé et al. (1998) provide a treatment system for urban stormwater designed to meet treated water standards suitable for bathing.

Filtration/sorption

Sansalone and Hird (2000) reported the results of a prototype partial exfiltration reactor (PER) to remove metals such as lead, cadmium, copper, nickel, zinc and chromium from stormwater runoff. The PER proved effective at removing these metals from the runoff influent. Clark (2000) conducted a pilot-scale study on the ability of several potential filtration media for treating pre-settled urban stormwater runoff. The results of the study showed that modeling pollutant removal in traditional pre-settled stormwater runoff will be difficult because the low concentrations of many pollutants are near the removal limit of many of the filters. Clark also investigated modeling equations for the removal of solids by filtration from stormwater runoff. The model equations that fit the data were similar to the power loading equation proposed for the sand filters in Lakewood, Colorado. This project also investigated the effects of anaerobic conditions on pollutant removal by four of the media: activated carbon, sand, compost and peat moss. The results were that most of the previously-sorbed metals would not be released if the water in the filter turned anaerobic; however, many of the nutrients would be released and washed off the filter during the next storm event.

Sala and Hensch (2000) tested the ability of silica micro encapsulation (SME) for the treatment metals-contaminated wastewater. They found that the technology has potential and they proposed that it could be used to treat stormwater runoff such as by injecting it into a runoff flow stream. The end result was that the metals were permanently stabilized and the SME material could be disposed of properly once its capacity was exhausted. Wigginton and Lenhart (2000) reported the results of using an iron-infused resin for the removal of phosphorus from stormwater runoff. Testing of the iron-infused resin in the Stormfilter™ cartridge showed 38.6% removal of dissolved phosphorus, 44.9% for total phosphorus and 78.6% for total suspended solids. Increased removals were observed between test cycles, indicating that increased oxidation of the iron occurred which provided additional sites for phosphorus adsorption.

Sansalone (1999) conducted detailed tests of a partial exfiltration trench (PET) for passively treating highway runoff at a test site in Cincinnati, Ohio. Runoff treatment in the PET occurred primarily by sorption and filtration. Media in the PET was expected to last more than 10 years. The mass pollutant removal efficiency generally exceeded 80% during the one year of tests. Exfiltration from the PET to clayey glacial till soils also exceeded 30% for some runoff events. Stephenson et al. (1999) also described a pilot-scale stormwater runoff treatment system for highway runoff that used peat, sand, and rock to remove contaminants by sedimentation, filtration, and adsorption. Field-testing sites were located in Knoxville, Tennessee, and Frederick, Maryland. The primary goal of this investigation was the development and evaluation of practical remedial measures for treating highway runoff draining into sinkholes, where very rapid movement of surface runoff to the groundwater can occur. Urbonas (1999) presented a detailed description of the design approaches needed for effective sand filtration of stormwater. The approach uses the unit processes known to exist in urban stormwater runoff and within filter devices. The suggested design was based on hydraulic capacity of the filter media, which, in turn, was a function of the total suspended solids removed by the filter. Shibata (1999) reported on the performance characteristics of pipe installations with replaceable filters. The data collected included information on the quantity of sand and gravel trapped in the filter section, as well as the ability of the filter to concentrate pollutants from stormwater runoff.

A system that included settling tanks, sand and carbon filters, and an ion exchange unit treated stormwater runoff from an airport prior to infiltration (Vivona et al., 1998). A laboratory and parking lot investigation showed that porous pavements significantly reduced the volume of stormwater runoff, as well as the concentrations of undesirable constituents in stormwater. Asphalt pavement had increased petroleum products (e.g. phenols) possibly due to the interaction of acid rain with the asphalt pavement (James and Shahin, 1998). Laboratory experiments conducted over the past three years showed that activated carbon, peat moss, zeolite, and compost were efficient at removing toxicants such as organics and metals from the stormwater runoff and retaining them during subsequent flushings with distilled water (Clark et al., 1998a). Sand was found to effectively remove toxicants from runoff, but then released them in subsequent flushings. Field experiments evaluated several filtration media for stormwater infiltration and treatment potential (Clark et al., 1998b). An activated carbon and sand mixture showed the best overall removal, though a recommendation for settling of runoff prior to filtration is given. A two dimensional model was developed to assist in the design of infiltration systems for stormwater management (Guo, 1998). The model revised the Federal Aviation Administration method to predict the detention storage volume by maximizing the volume difference between the design storm runoff and the basin infiltration rate.

A filter with humic media was discussed for the treatment for stormwater runoff (Kratch, 1997b). The media, which contains a processed leaf compost, removes 90% of SS, 85% of oils and grease, and 98% of metals.

Treatment train systems

Pitt (1996) discussed the utility of the SLAMM stormwater quality model in designing watershed-scale pollution reductions and evaluated technologies for control of stormwater, such as catchbasin retrofit devices, a multichambered treatment train (MCTT) for critical source areas, and different filtration media. The Multi-Chambered Treatment Train (MCTT) was developed for removal of stormwater toxicants from critical source controls (Pitt et al., 1999). The MCTT was an underground device that has three main chambers: an initial grit chamber for trapping of the largest sediment and release of most volatile compounds; a main settling chamber (providing initial aeration and sorbent pillows) for the trapping of fine sediment and associated toxicants and floating hydrocarbons; and a sand and peat mixed media “filter” (sorption-ion exchange) unit for the reduction of filterable toxicants. A typical MCTT requires between 0.5 and 1.5% of the paved drainage area, which was about one-third of the area required for a well-designed wet detention pond. The research report described extensive development of the MCTT, including much stormwater treatability information that can be used by others who want to enhance performance of conventional stormwater control devices. A pilot-scale unit was tested in Birmingham, Alabama, at a large parking lot. During monitoring of 13 storms, the MCTT was found to have the following overall median reduction rates: 96% for total toxicity, 98% for filtered toxicity, 83% for SS, 60% for COD, 40% for turbidity, 100% for lead, 91% for zinc, 100% for n-Nitro-di-n-propylamine, 100% for pyrene, and 99% for bis (2-ethyl hexyl) phthalate (Pitt et al., 1998b). Corsi et al. (1999) reported the results of a full-scale test of the MCTT at a public works yard in Milwaukee, WI, conducted by the USGS and the WDNR. Monitoring of 68 common and toxic constituents was conducted during 15 storms having rain depths ranging from 0.17 to 1.4 inches in depth, over a five-month period. Very high reductions were found for all particulate-associated pollutants (reductions of 98% for SS, 88% for total phosphorus, and 91% for total ZN, for example), and somewhat less reductions for dissolved pollutant fractions (13% TDS, 78% dissolved phosphorus, and 68% for dissolved ZN, for example). The WI DNR also conducted a full-scale test of an MCTT at a 4-acre municipal parking lot at Minocqua, in northern Wisconsin, with similar high level removals noted.

Airport Deicer Control

Periello et al. (1999) described a biological treatment system for treating stormwater runoff that was contaminated with de-icing fluid at the Syracuse (New York) airport. During winter deicing operations, spent deicing fluid, combined with storm runoff, was collected and held in large treatment lagoons. When warmer weather arrives and deicing operations cease, the collected deicing fluid and combined stormwater runoff (deicing runoff) were treated in aerobic lagoons to reduce the BOD in the deicing runoff to levels suitable for discharge to the local receiving waters. Safferman et al. (1999) studied the treatment of stormwater contaminated with ethylene glycol originating from airport deicing operations using a bench-scale subsurface microbiological contactor. Zitomoer et al. (1999) discussed the use of anaerobic co-digestion of aircraft deicing runoff and municipal wastewater sludge. The high COD runoff can lend organics for increased methane production and the oxygen demanding constituents in propylene glycol deicing fluid were found to be readily converted to methane, with neither effluent BOD₅ nor TKN concentrations higher in co-digestion systems as compared to a conventional digester. They concluded that existing municipal digesters could be employed to convert the seasonally-generated deicing fluid organics to methane that could be used to run equipment or generate electricity.

Combined Sewer Overflow/Sanitary Sewer Overflow Control

Combined sewer overflows (CSOs) and sanitary sewer overflows (SSOs) continue to be an important source of water pollution throughout the world. The analysis of CSO abatement alternatives often proceeds in an evolving manner. Landside models are generally used to determine which outfalls need CSO abatement, sometimes in conjunction with receiving water quality models. Once CSO outfalls needing abatement are identified, an optimal level of abatement needed to achieve water quality standards can be determined. With the required abatement level determined, various methods of achieving that level can be explored. Many small-to-medium-sized communities with combined sewer systems are faced with regulatory mandates to prepare long-term CSO control plans.

Brilhante et al. (2000) described the use of USEPA’s Storm Water Management Model (SWMM) in CSO analysis. As a project proceeds through planning and design of CSO abatement, the model would be refined to test alternatives and set the detailed specifications. Lyon (2000) advocated a systematic approach to CSO control systems. The first step would be to examine wastewater treatment plant flows during dry and wet weather periods to determine the effectiveness of the CSO control system in capturing base sanitary flows. Second, all available data should be examined to determine how the

system is affected by wet weather events and the probable relative magnitudes of CSO loadings to area receiving streams. This approach was successfully used in Charleston, West Virginia, to identify a low-cost solution to minimize CSO loadings to the Kanawha River. The City of Niagara Falls, New York, also used a step-wise approach in dealing with levels of infiltration and inflow in its collection system, which are creating service problems for residents and impacting the City's ability to redevelop its eastern portion. The City sought the cooperation of state officials when addressing the problem which seemed to keep from imposing undue financial hardships on the ratepayers and residents (Roll and Benson 2000).

Gomis et al. (2000) analyzed the factors involved in the response of an urbanized drainage basin with a combined sewer system to a rainfall event. In the case of moderate and heavy rainfall, the coefficient of flow was independent of the rain characteristics and was close to the imperviousness coefficient. For lighter rainfall, flow was determined by the initial surface state of the drainage basin. Lindholm and Nordeide (2000) evaluated the relevance of different methods and criteria for choosing the best system to solve a CSO problem in Oslo, Norway. A simple EIA analysis with a pragmatic choice of criteria was found most suitable for choosing between conventional or nature-based solution. Marsalek and Giulianelli (2000) presented a comparative analysis of urban drainage challenges in Italy and Canada. Canada offered stormwater management practices and satellite CSO treatment; Italian contributions included effective layouts of distributed CSO storage and operation of such systems in real time. The City of Livonia, Michigan used Geographic Information Systems (GIS) technology to enhance the implementation of its illicit discharge elimination program. As a result, record keeping was improved, problem areas identified earlier, and joint efforts with surrounding communities and agencies in Livonia simplified (Rohrer and Beckley 2000). Smith et al. (2000d) presented observations and determined causes of increased odor production and release in recently separated collection systems. The authors also presented the corrective actions which have been shown to reduce these odor effects. Hydraulic/hydrologic modeling was conducted using the EPA SWMM model in support of the design of a CSO consolidation/relocation project in South Boston. The SWMM model was used for design, facilities planning. The model was refined and recalibrated as needed to provide greater confidence in the design flows. A 50-year storm that occurred during the flow monitoring period provided confidence that the recalibrated flows were appropriate for use as design criteria for the CSO consolidation/relocation conduit (Walker et al. 2000b). A detailed hydraulic model was used to simulate alternative flows scenarios to and through the treatment plant as part of a city-wide CSO Strategy in Edmonton, Alberta, Canada (Ward et al. 2000).

Buchholz et al. (2000) used a computer model to evaluate the performance of a CSO retention treatment facility in Michigan. To comply with the requirements of the Federal Clean Water Act, improvements to the system were accomplished by additional storage of CSO, removal of storm water inputs to the treatment facility, and maximization of the use of the existing interceptor system. The regulatory impetus for this work was Michigan's CSO Policy, which states that CSOs must be eliminated or controlled to protect designated uses at times of discharge. The level of control may be determined either by a water-quality based demonstration or by accepting a presumptive level of treatment described in terms of a retention/treatment structure (Cowles 2000). Six years after the EPA's 1994 CSO Policy was issued, only two of the 30 States with CSO municipalities have taken actions to implement the water quality provision of the federal CSO policy. Conditions in urban areas and other point and non-point sources of pollution may make current water quality standards in some urban waters no longer appropriate or unable to be met, regardless of CSO controls that are implemented. Dwyer and Huang (2000) have advocated a review and revision of existing water quality standards in order to save unnecessary expenditures, ensure that proper water uses are maintained, and significantly improve the implementation of the water quality-based provisions. The expectation of the CSO Control Policy was that long-term control plans (LTCPs) would be developed to meet water quality standards (WQS) and, where appropriate, states would revise their WQS to reflect the difficulty in achieving compliance with current bacterial standards in urban areas during wet weather events. Slack and Nemura (2000) discussed the difficulties CSO communities face in obtaining revisions to WQS as part of developing LTCPs that are cost-effective and protective of water quality and human health.

Rowe (2000) presented an overview of SSO control strategies to management and engineering staff who represent a National Pollution Discharge Elimination System (NPDES) permittee. The U.S. EPA's Environmental Technology Verification (ETV) Program was established to overcome the numerous impediments to commercialization of innovative environmental technologies, particularly the lack of credible performance data. Stevens and Frederick (2000) described the ETV approach and two recently initiated pilot programs for verification testing of source water protection technologies and wet-weather flow technologies. USEPA is currently completing the issuing of a SSO Rule that will add control of SSO to the NPDES permit requirements. Lai et al. (2000) provided a preview of the rule and described the advantages of employing a collection system modeling approach for capacity analysis and development of the SSO mitigation plan. Historically, EPA and the States have allowed municipal facilities to bypass peak wet weather flows

around the secondary treatment process, to disinfect the rerouted flows, and then blend the peak flow with the other, more highly treated, effluent. A reinterpretation of the federal “bypass” rule by some regulators includes the position that if rerouting causes any of the waste stream to skip a treatment process, bypassing is illegal (Hall et al. 2000).

Many large-scale SSO, CSO and WWF control programs are underway worldwide. The city of Evanston, Illinois, successfully undertook a large-scale project to control basement flooding from combined sewer backups by limiting the entry of wastewater to the sewer system to exactly the quantity that matches the conveyance capacity. Figurelli et al. (2000) evaluated the performance of the program against the following criteria: technical hydraulic performance (basement backup and street ponding performance), citizen perception of performance, maintenance concerns and costs, capital costs, level of construction disruption, and public acceptance. The City of Saginaw, Michigan completed the second phase of a comprehensive CSO control project that was required to meet NPDES Permit requirements. Hubbell and Phillips (2000) have provided information on the historical background of the existing Saginaw sewer system, NPDES permit issues, project planning requirements, design considerations, construction, operations, and performance. A multifaceted project including highway improvements, development of waterfront parks, and water quality improvements resulting from CSO abatement was begun in New York, New York. According to Kloman et al. (2000), the New York City project has served as an example of inter-agency cooperation to benefit the community and environment.

Kok et al. (2000) reviewed the work of Canada's Great Lakes 2000 Cleanup Fund, which is administered by Environment Canada, in supporting the development and implementation of cleanup technologies to control municipal pollution sources, to clean up contaminated sediments, and to rehabilitate fish and wildlife habitats. The Urban Drainage Program has been instrumental in advancing the state of the art in CSO and stormwater management in Ontario (Kok et al. 2000). The Philadelphia Water Department's (PWD's) CSO program goal is to improve and preserve the water environment in the Philadelphia area and to fulfill PWD's obligations by implementing technically viable, cost-effective improvements. The PWD's strategy to attain these goals has three primary phases (currently being implemented): (1) continued implementation of a Nine Minimum Controls comprehensive program; (2) planning, design, and construction of 17 capital projects to reduce CSO volume and frequency; and (3) a commitment to complete comprehensive watershed-based planning and analyses to identify the actions needed to further improve water quality and quantity dynamics in local water bodies (Marengo 2000). In 1998 the City of Rockland, Maine, began a major capital improvement program of its wastewater collection and treatment system and included provisions for high-rate treatment of CSO flows (Freedman et al. 2000). Clifford (2000) reviewed efforts by the English and Welsh water industry to solve urban CSO pollution problems and to develop guidance for integrated stormwater management. The Northeast Ohio Regional Sewer District has undertaken the lead role in CSO management in the metropolitan Cleveland area and has recommended a CSO control plan. This plan includes several technologies that will maximize use of the existing system, as well as new facilities for CSO control (Matthews et al. 2000). Various public utilities in Broward County, Florida have implemented sanitary sewer rehabilitation programs which are expected to include a minimum of at least 7,796 repairs (Larsen and Garcia-Marquez 2000). Seigle et al. (2000) reported on the negotiated long-term CSO control plan for Manchester, NH. An inventory and structural evaluation of CSOs in towns (greater than 30,000 inhabitants) in Slovakia was carried out during a three-year joint research project of the Water Research Institute and the Department of Sanitary Engineering of the Slovak Technical University in Bratislava (Sztruhar et al. 2000).

Riverine litter occupies a spatial and temporal position in any systematic analysis of river systems and was a problem that was increasing in scale. Quantifiable source factors of litter in the river Taff, South Wales, United Kingdom, system were found to be mainly two - sewage inputs through CSO and fly tipping. Whilst sewage-derived material constituted approximately 23% of all items on the river Taff, large quantities of waste, especially plastic sheeting, originated from fly tipping sites (Williams and Simmons, 1999). If the storage in the rain water tanks can be used to flatten the rain water runoff, rain water tanks can have an additional benefit. The effect of rain water tanks on the CSO emissions was therefore investigated with a reservoir model. Compared with storage in the combined sewer system or at the overflow, storage in rain water tanks will be more efficient in reducing the overflow emissions (Vaes and Berlamont, 1999). Milina et al. (1999) described the results of an integrated model development and its application to the Hovringen wastewater system in Trondheim, Norway. Major model development needs concern the integration of sewage production, transport and treatment simulation, the interface with existing databases and the possibility of simulating processes that were controlled in real time. The developed integrated model has been used to design the treatment process as well as static and dynamic measures in both the catchment and the sewer system.

The use of sand and other media filters was gaining acceptance in the field of urban stormwater structural best management practice. Much work has been done to develop local design guidance, such as in the State of Delaware and

in Austin, Texas. The suggested design of the media filters for stormwater runoff treatment was based on hydraulic capacity of the filter media, which, in turn, was a function of the total suspended solids removed by the filter (Urbonas, 1999). Walesh et al. (1999) provided a discussion of the use of on-street storage as an effective means to control stormwater runoff. It focuses on the success achieved by using street storage in two communities in Illinois and includes a description and evaluation of how this technology eliminated surcharging and basement flooding, complied with regulations and proved to be a cost-effective solution which earned public support.

As a demonstration project, the Auckland Regional Council had designed and constructed a filter device to treat stormwater from a 3000 m² carpark. Eight sand filters were installed in 1993 to provide stormwater treatment at a new Alaska Marine Lines, Inc. barge loading terminal along the Duwamish River in Seattle, Washington (U.S.A.). Constructed according to the "Delaware" design, each consists of a settling chamber where relatively large solids can settle before the flow passes over the weir onto the sand for filtering. A performance study monitored the flow rate through two sand filters and the water quality of inflow and outflow (Horner and Horner, 1999). Because the Urban Community of Bordeaux had been hit by important floods in 1982, it was decided to set an efficient management system to control stormwater flows. Studies have showed the significant impact of discharged effluents on the environment, especially with regard to the contribution from CSO. Therefore, it was of importance to improve the management of the sewer system during rain weather and to foresee the design of new storage structures and new treatment plants to integrate the environmental protection target (Briat et al., 1999).

Overviews of WWF controls were provided by two papers. Buriean et al. (1999) summarized a comprehensive historical literature review, highlighting the development of WWF management from ancient times to the present. The relationship between past developments, the current state, and the future of WWF management were addressed by identifying several lessons learned. Barner (1999) discussed the problems associated with stormwater management in a karst terrain in Springfield, Missouri. The lack of recognition of sinkholes as integral parts of dynamic hydrologic systems may result in problems with on-site/off-site drainage.

CSO control planning. Bontus et al. (1999) described Edmonton's proactive long-term CSO control plan, which brought the opinions of stakeholders, including Alberta Environmental Protection, river user interest groups, the local health authority and a representative of the University of Alberta, to the technical process, and ensured that their input was considered in developing the plan. Newhouse et al. (1999a) described the development of a long-term CSO abatement plan by the City of Richmond, Virginia. The protection of recreational uses of the James River was a priority for the city. City officials at Richmond, Virginia, agreed to a joint venture with the Richmond Riverfront Development Corporation that would eliminate CSO and restore the Haxall/Kanawha canal system. Engineers not only had to ensure that each project's requirements and objectives were met, but also address technical and environmental issues without compromising the area's recreational and commercial needs or diminishing its aesthetic appeal or historic character (Newhouse et al. 1999b). Based on interviews conducted during 1998, Slack and Freedman (1999) compared and contrasted current state-to-state and community-to-community differences in efforts to control SSO. The variability in abatement efforts were tied into the proposed language for EPA's forthcoming Federal Register notice that will clarify NPDES requirements for municipal sanitary sewer collection systems and SSO.

Other authors addressed the steps taken to achieve CSO and SSO control. In the early 1990s, the City of Auburn, New York, was faced with the challenge of achieving CSO abatement and sanitary and interceptor sewer overflow (SSO) elimination in its extensive, aged sewer system and achieved their overflow abatement goals by: (1) quantifying and characterizing sewer overflows to provide a basis of design for abatement-related system improvements; (2) selecting a principal approach of conveyance of excess WWF to a centralized high-rate treatment facility for a majority of the sewer system; and (3) re-evaluating and applying alternative technologies to select portions of the sewer system to minimize project costs. Li and Banting (1999) presented a case study using a GIS planning tool for stormwater quality management in urbanized areas. The planning tool comprised five steps: (1) definition of stormwater retrofit goals and objectives; (2) identification of appropriate retrofit stormwater management practices; (3) formulation of stormwater retrofit strategies; (4) evaluation of Strategies with respect to retrofit goals and objectives; and (5) selection of stormwater retrofit strategies.

Markowitz et al. (1999) described the conceptual ideas, cost analysis and other issues that effect implementation of watershed controls within the scope of a CSO control plan. Osaka City's (Japan) major measures for improving CSO include: (1) leading as great a volume of pollutants as possible to WWTP in dry weather to avoid the pollutant accumulation in sewers; (2) storing first flush, which contains a large volume of pollutants, for treatment at WWTP after rainfall; and (3) treating WWF directly. Shiomi (1999) discussed the methods used to achieve these measures and reports

the conclusions drawn from the cost-benefit analyses. A 5-year cooperative study of the Cumberland River at Nashville (Tennessee) allowed Nashville to alter its CSO control plan, eliminate two major detention tanks, and save \$106,000,000. The study showed that neither DO depletion nor toxic material discharges were a problem, and that a fecal coliform bacteria problem would not be solved by planned detention tanks, or even by eliminating all CSO (Thackston and Murr, 1999). Today conventional planning and reconstruction of both the drainage network and the treatment plant for the same urban catchment was usually subdivided into two nearly independent parts. Walther and Rohlfing (1999) demonstrated optimal design of a combined sewer system and sewage treatment plant for a German city with 500,000 inhabitants by simulating the operation of both systems simultaneously, and costing each system based on a variety of possible configurations of the other.

Additional published accounts of the experiences of various municipalities in controlling CSO and SSO provide guidance for those beginning a WWF control program. The City of Auburn's (New York) sewer overflow abatement program summarized by Gorthey et al. (1999) can serve as a guide and source of information for other municipalities faced with achieving sewer overflow abatement. Igwe et al. (1999) focused on design and operational issues encountered during the evaluation of the Rouge River National Wet Weather Demonstration Program, which includes the construction of nine CSO detention basins of varying sizes and design. The City of Akron (Ohio) has successfully implemented the demonstration approach to CSO control and has supported controls that will result in measurable improvement of recreational use, aquatic life use and aesthetics of the receiving streams, including concepts other than traditional collection system alternatives. These include riparian setbacks in undeveloped areas, stream restoration, linear parks or greenways and artificial riffles for stream aeration. Merritt and Wilkinson (1999) presented studies on wastewater collection systems, including: collection system design and construction; wet weather control; infiltration and inflow; SSO; innovations in sewers and collection systems; infrastructure modeling; sewer pipe maintenance and rehabilitation; sediment transport, deposition and erosion in collection systems; and sustainable development. Protopapas (1999) reported the methodology used by New York City to abate pollution from CSO in the receiving harbor waters based on a case study for the East River facility planning. The approach integrates water quality studies, facility planning, environmental assessment and public participation. Wong et al. (1999) presented a case study that covers the planning, design and operation aspects of implementing a pumping drainage system into the existing drainage system at the Pasir Baru residential area in Kuala Lumpur (Malaysia) city. Zettler et al. (1999) discussed how the City of Fort Wayne, (Indiana) has successfully applied a consistent set of GIS-based information management tools to support both their CSO planning efforts and preliminary design process.

Both typical and non-traditional areas must be considered in order to eliminate SSO and prevent future, potential overflows from occurring. Community and wastewater leaders must change the influences which allowed SSO in the first place — insufficient funding, short term thinking, inadequate maintenance, insufficient inspection, lack of widespread understanding of the issues and other such factors (Jurgens, 1998). The town of Smithville, Tex. (Myers, 1998) demonstrated how a small city with a population under 5 000 can address and implement sound water-quality practices as an integral part of handling stormwater runoff and implementation of an overall drainage plan. A case study in the Great Lakes region of Can. illustrated the planning process for development of stormwater retrofit strategies for existing urbanized areas using downspout disconnection, oil/grit separators, exfiltration systems, and stormwater ponds (Li et al, 1998). Through a \$1 billion wastewater improvement program the Miami-Dade Water and Sewer Department (Fla.) achieved a 56% reduction in the occurrence of SSO over a three year period and a 66% reduction in the total volume of SSO (Cardozo et al., 1998). The department also met 800 other milestones, some of which carried stipulated penalties of up to \$10 000 per day for noncompliance.

To meet a 2001 deadline to eliminate SSO, Fort Worth, Tex. commenced a tunneling project to redesign its sewer system in 1995 (Sahu et al., 1998). The tunnel would result in a shorter, more direct route for the sewer and offered a potential savings of \$4.5 million over feasible open-cut routes. Richmond Va., which was required to control two CSO points by retention storage for one month design storms by the Va. Water Control Board, chose to install tunnels because of the minimal disruption during construction and their low environmental impact (Harsen et al., 1998). The 3 960 m long and 3.35 m diameter North Dorchester Bay consolidation conduit will provide complete capture and relocation of discharges from seven CSO outfalls tributary to Dorchester Bay and the bathing beaches of South Boston, Mass. (Heath et al., 1998b and 1998c). Columbus, Ohio implemented the minimum control of maximizing collection system storage as part of the CSO Operation Plan (El-Hosseiny et al., 1998b). Investigations of the Chestnut St. Regulator indicated that a system separation may not reduce the number and duration of overflows from the combined system and that separation may have a negative impact on the receiving stream.

The MWRA's recent CSO facilities plan provided that floatables control technologies be applied to 48 CSO outflows (Walker et al., 1998). After testing several floatable control mechanisms, the authority found baffles most cost effective, though little data was available about baffle performance or maintenance. The Boston Water and Sewer Commission undertook a study of alternatives to the MWRA's proposal of a screening and disinfection facility to deal with CSO and recommended all of the combined sewers along the Stony Brook Conduit be separated (Keohan, 1998). The MWRA accepted this alternative and revised its CSO plan. A cooperative project with the U.S. EPA and the Association of Metropolitan Sewerage Agencies to track improvements and benefits associated with CSO control involving "stakeholders" interested in CSO control identified the use and benefits of performance measures and recommended a process for selecting among 24 practical and useful performance measures (Sullivan et al., 1998). Turner and Reindel (1998) proposed the establishment of a national database on CSO outfalls.

The U.S. EPA and Tex. Natural Resource Conservation Commission mandated that Houston, Tex. control wet-weather overflows caused by excessive I/I during rainfall events by December 1997. A long-term simulation model was used for the construction of wet-weather facilities as part of the SSO control strategy for three service area collection systems (Maa et al., 1998a). Relief of Houston's collection system bottle necks for the short duration, high intensity thunder storms of the Gulf Coast Region was found to be a more cost-effective alternative than rehabilitation (Maa et al., 1998b). Based on 91 sewersheds worldwide the average reported I/I reductions were 49% of peak I/I rate with a standard deviation of 25%. Twelve projects reported reductions greater than 75% (Keefe, 1998). Racine, Wis. (Marman et al., 1998) constructed diversion facilities with storage and partial treatment. The facilities prevented a cumulative SSO discharge volume of 3 million m³ (783 MG) between 1993 and 1998 and actual SSO discharge was limited to 0.05 million m³ (14 MG). A study to set up a long-term wet-weather control plan by the NORSD in the Westerly District of Cleveland, Ohio discovered problems with manhole invert plates, system blockages, and located sources of dry-weather flow (Bingham et al., 1998).

A five-year study confirmed the benefits of the original automation of the Lima, Ohio combined sewerage system by maximizing their CSO system storage and minimizing the impact of storm overflows on receiving waters. An upgrade provided additional benefits including decentralized communication, data accessibility, and additional control capabilities (Nye et al., 1998). Applications in the U.S., Can., and Fr. of Global Predictive Real Time Control (GPRTC) which can optimize and aid design of more efficient CSO control were described by Villeneuve and Pleau (1998). Perdek et al. (1998) discussed both international and national state-of-the-art technologies related to storage and sedimentation treatment for CSO. Harold et al. (1998) provided guidelines for accurate data from SSO and CSO monitoring based on the experience of major SSO and CSO monitoring projects conducted.

Gaffoglio et al. (1998b) used NYC's Inner Harbor CSO Facility Planning Project to demonstrate the cost effectiveness of maximizing WWF to the WPCP. This strategy has led from 74 to 88% capture of CSO. The East Bay Municipal Utility District and local communities eliminated sewer overflows to San Francisco Bay, Calif. by increasing capacity to its treatment plant, installing seven miles of large-diameter sewer interceptors, and increasing storage among other techniques (Housen and McCormick, 1998). The city and county of San Francisco, Calif. has, since the completion of the combined sewer system control structures, achieved a reduction in the number of overflows to the shoreline, and an associated reduction in the elevated bacteria counts and days of beach postings for public health concerns (Foree and McGregor, 1998). The WPCP of combined sewer systems are designed to operate satisfactorily for the design case and consequently all plants maintain reserve capacities for most of the time, even during high stormwater inflows. Müller and Krauth (1998) reported of the development of an automatic control strategy to manage the wastewater flow to a WPCP according to its actual treatment capacity. Winnipeg, Can. initiated a CSO management study in 1994 to establish a cost-effective prioritized implementation plan for remedial works (Rempel et al., 1998). The study indicated that the use of inline storage in 43 individual combined sewer districts covering roughly 10 000 ha is the most effective first step in the wet-weather pollution control plan. The database MED-MEASURE was used for in-sewer and CSO online monitoring in the city of Paris (Fr.) where more than 100 points were monitored simultaneously for COD, BOD, and SS (Tremblay et al., 1998).

Schaefer (1997) discussed that the challenge of stormwater management will be an environmental challenge in the 21st Century. New partnerships between environmental engineers and other professional groups have to be established to minimize diffuse long-term deposition of hazardous substances (Boller 1997). In Wayne County, Mich., animation was used effectively as a public information/presentation tool on the Rouge River Watershed National Wet Weather Demonstration Project to illustrate CSO and water-quality impacts (Shaw and Murray 1997).

A fast-track approach was taken in the construction of a 60-ft high surge well around an existing 108 in. outfall downstream of the effluent pump station in response to Tropical Storm Gordon in the City of Miami, Fla. (Chorlog *et al.*, 1997). Guderian *et al.* (1997) showed that rigid flow management for a sewer and treatment plant did not always fulfill the total emissions reduction goals for CSS. Sanders (1997) reviewed results of a detailed study of six WWTP facilities in Missouri that were impacted by the Great Flood of 1993 and concluded design engineers could probably have prevented many of the negative impacts.

The cities of St. Paul, South St. Paul, and Minneapolis, MN recently completed their 10-year, \$331-million sewer-separation program for CSO control (*Water Environ. & Technol.*, 1996b). Included in this program were the installation of 189 mi of storm sewers, 11.9 mi of sanitary sewers, paving of 168 mi of oiled streets, and disconnection of roof leaders at 21,900 residential properties.

Innovative CSO controls - source controls.

CSOs often have been treated at the overflow point. Overall, the operating experience of the nine CSO control facilities on the Rouge River (Detroit, Michigan) has provided valuable information for designing future phases of CSO control on the river and for communities engaged in CSO control in other watersheds (Johnson *et al.* 2000). Andoh and Saul (2000) outlined recent developments in CSO technologies, particularly screening devices, and described the characteristics of the ideal intermittent wet-weather screening system. The authors then describe the development and evaluation of a novel self-cleansing CSO device - The Hydro-Jet Screen™. Averill and Gall (2000) examined the implications of intermittent loadings on operation of treatment systems and outlined a strategy for the planning and design of CSO, SSO or stormwater treatment systems. In the City of Niagara Falls, New York, options other storage for CSO control were evaluated because of the high cost of constructing a storage facility. High rate treatment by means of vortex separators was considered an attractive option after preliminary settling column tests showed that the settling characteristics of the CSO were amenable to this treatment (Cheung *et al.* 2000). Underflow baffles have become popular for intercepting floatables in CSOs, but largely have been untested. Cigana *et al.* (2000) reported the results of a study of floatables capture by 17-meter-long basin at various flowrates. Their data suggested that capture efficiency of existing underflow baffles in an overflow chamber will be very low whenever the horizontal velocity is greater than 0.30 m/s or 1 ft/s. Inappropriate operation of a partly-lowered gate in a new overflow structure caused the interruption of a 100-year old brick interceptor sewer in the Sea Cliff area of San Francisco during an intense, but not extraordinary, rainstorm (Medley 2000).

Clegg *et al.* (2000) presented projects for removal of rainwater inflow sources on private property from combined and sanitary sewer systems in Lansing and Port Huron, Michigan. Keys to success for these projects included property owner understanding, city identification of inflow sources, free advice and site visits, tracking and follow-up, flexibility on removal method, and ordinances to help enforce inflow removal on all private properties. Detroit, Michigan planned the Conner Creek Pilot CSO Control Facility to provide skimming, settling, and disinfection to meet the daily and monthly fecal coliform limits of 400 and 200 colony forming units (cfu) per 100 milliliters (ml), respectively (Fujita *et al.* 2000a). If this 30-million gallon "pilot facility" can meet the fecal coliform limits, it likely would provide significant cost savings in CSO treatment (Fujita *et al.* 2000b). The CDS method performs a liquid/solid separation and consists of a stainless steel perforated and deformed separation plate placed in a hydraulically balanced separation chamber. Louisville and Jefferson County MSD (Kentucky) have been a demonstration site for one of the first CSO applications of CDS technology (Gratzer 2000). The Detroit (Michigan) Water and Sewerage Department, in developing the Long Term CSO Control Plan, has recommended an innovative screening and disinfection approach to reduce CSO impacts on the Detroit River. Underground structures were designed for two pilot facilities to convey the flows through 4mm raked bar screens, and then direct the solids to the wastewater treatment plant through a side stream, thus eliminating the need for residuals to be collected and transported from remote facilities (Rabbaig and Neibert 2000). Zaccagnino *et al.* (2000) reported on several end-of-pipe CSO controls implemented by the New York City Department of Environmental Protection to reduce CSO impacts on Flushing Bay.

A case study of the development, implementation, and evaluation of a capital-works program aimed at reducing the contribution of rainfall-induced-extraneous flow from an existing sanitary-sewer-collection system by nonstructural means was presented by Rowe *et al.* (1997). In Lower Paxton Township, Pa., > 60% of the I/I was identified as coming from private sources (Elliot *et al.*, 1997). Besides rehabilitation of public sewers, where necessary, the town developed an ongoing plan to seek out and correct I/I from private sources. The Miami-Dade Water and Sewer Department of Florida developed a very comprehensive Infiltration/Exfiltration/Inflow-reduction program that is one of the largest and most successful in the country (Aguiar, 1997).

Sanitary-sewer flows and wastewater-treatment-cost effectiveness were compared five years before a downspout-diversion program and 15 months after the program. The diversion program yielded a 25% reduction in mean-flow volumes and a significant reduction in wastewater-treatment costs (Kaufman and Wurtz, 1997).

Innovative WWF control strategies include using rainwater and runoff for potable uses and controlling gaseous emissions from combined sewer systems. Herrmann et al. (1999) reported on a four-story apartment building which was renovated using an innovative water concept. Roof runoff used stored for use in flushing toilet, and excess runoff was infiltrated, allowing the building to be completely unconnected from the stormwater sewer. The authors showed that independent from the soil and the available space it was possible to restore the natural water balance again by combination of rainwater use and subsurface infiltration. Lausten et al. (1999) described the use of a biofilter to capture and control hydrocarbon odors including VOCs from a combined sewer and an interceptor sewer in Philadelphia, Pennsylvania. The biofilter has proven to be a successful process application for treating VOC compounds from the air stream. Lim and Lim (1999) described a unique scheme to implement urban stormwater pond collection systems for potable water use in Singapore. Close monitoring and control of pollution through the adoption of stringent anti-pollution measures and enforcement actions have resulted in the collection of generally good quality raw water from these urbanized catchments with very low levels of heavy metals and low coliform counts as compared to raw water from largely forested catchments.

Source control of WWF aims to reduce overflows by reducing inputs to the system. Schmitt et al. (1999b) described the correct procedures for inclusion of source control measures in urban stormwater management into the Gemnan design procedure A 128. Results obtained by long term pollution load simulations emphasized the need to review existing guidelines. Williams et al. (1999) reviewed a partnership between the Louisville and Jefferson County Metropolitan Sewer District (MSD), the Louisville Education and Employment Partnership (LEEP), and the Jefferson County Public Schools (JCPS) designed to provide an opportunity for students and teachers to work in a paid summer internship with consulting engineering firms that contract with MSD, and assist MSD in collecting information regarding wet weather issues such as misconnected downspouts, sump pumps, and leaky sanitary sewers. The program, which has been successful for five years, provides a quick and cost effective investigation that identifies inflow source reduction opportunities for mitigation of property damage and SSO.

Walesh et al. (1999) provided a discussion of the use of on-street storage as an effective means to control stormwater runoff and CSO in two communities in Illinois. This technology eliminated surcharging and basement flooding, complied with regulations, and proved to be a cost-effective solution which earned public support. Lachmayr and Schofield (1999) focused on the fieldwork techniques used to identify specific inflow sources from large buildings in the area served by the Boston Water and Sewer Commission, Massachusetts. Vaes and Berlamont (1999) examined the effect of rainwater tanks on CSO with a reservoir model. Compared with storage in the combined sewer system or at the overflow, storage in rainwater tanks will be more efficient in reducing the CSO discharges (Vaes and Berlamont, 1999).

Sewerage repairs and I&I control..

The condition of a combined or sanitary sewer influences overflows from the system, and sewer inspection and prioritization of repair efforts are important parts of overflow control. Continual improvement and streamlining of an inspection and evaluation program for the condition of a system of interceptor sewers and CSO facilities in the Cleveland (Ohio) metropolitan area resulted in an innovative and widely applicable approach to locating, identifying, and inspecting interceptor and CSO facilities. This approach significantly reduced field time and greatly increased the accuracy of the data collected (Krizmanich et al. 2000). Hahn et al. (2000) described an expert system, Sewer Cataloging, Retrieval and Prioritization System (SCRAPS), that prioritizes sewer inspections to target information collection from critical portions of the network. Kelly et al. (2000) reported on a process successfully used in New Orleans (Louisiana) to quickly and effectively address manhole rehabilitation needs. This process consisted of standardized data collection, computerized decision-making and implementation of appropriate rehabilitation methods. Merrill et al. (2000a) presented a tool to help utilities prioritize inspection of sanitary sewers to overcome problems/limits of available data and the limited ability to inspect and repair or replace sewer infrastructure. In validation exercises using case studies supplied by the experts, the tool was shown to outperform a group of experts in quantifying the need to inspect (Merrill et al. 2000b). In 1995, the Washington Suburban Sanitary Commission, which is located in Montgomery County and Prince George's County, Maryland launched a 4.5-year, multimillion-dollar I/I analysis and sewer system evaluation survey. The paper by Nguyen et al. (2000b) summarized the results of the Rock Creek I/I Analysis project, described the tools developed to analyze the voluminous amount of data, and discussed the method used to prioritize the repairs of the identified defective manholes and pipelines. Pomroy et al. (2000) reported on a statistical condition model that was used to forecast the future condition of selected small-diameter (4- inch to 10-inch) sewer pipes and to estimate necessary rehabilitation capital costs in the

Central Contra Costa (California) Sanitary District. The authors reported that condition modeling provided an efficient means to plan future expenditures and staffing requirements. A highly-accurate dye dilution testing protocol was developed and used by Stonehouse et al. (2000) to quantify flow meter accuracy in the Greater Detroit Regional Sewer System. Many meters typically considered to be accurate had errors of more than 30%, with some meters having errors exceeding 70%. Overall, the average initial system accuracy for system meters was observed to be $\pm 15.0\%$ of measurement with an overall bias of 6.1% (under-predicting flow). It was concluded that (1) there were observable accuracy differences between flow meter technologies; (2) objective standards like dye dilution testing were critical to good metering; (3) verifying installed accuracy was important, even for technologies considered to be highly accurate; and (4) the simplest technology that can be used often was the best.

Forbes (2000) examined the causes, diagnosis, impacts, and treatments for excessive infiltration/inflow (I/I), a significant cause of sanitary sewer problems, including SSO. Kurz et al. (2000) reported on a program in Nashville, Tennessee to improve system characteristics, recapture capacity, and reduce I/I so the sewers can carry the peak flow from their design storm without overflows. Accordingly, the authors recommended that sewer rehabilitation programs should include procedures to measure I/I removal effectiveness as a program progresses. A geographic information system (GIS) based system was developed to manage both sewer maintenance and I/I reduction programs. The system was designed to be used primarily for issuing work orders and responding to customer complaints, but it could also be utilized by engineers in conjunction with sewer line modeling needs (Shaffer and Greiner 2000). In 1992, Springfield, Missouri, began a long-term program of I/I reduction which included a comprehensive sanitary sewer evaluation, development of a hydraulic model, various manhole and pipeline renewal projects, and the addition of strategic relief sewers (Wade 2000). In Beverly Hills, Michigan, I/I into the sanitary system from public and private sources overloaded the sewer system and caused basement flooding and SSOs to local surface waters during large rain events. Sump pumps from residences were connected to the sanitary sewer system, so a project was undertaken investigate the effectiveness of removing sump pump connections to the sanitary sewer system in an effort to correct this I/I source. The results showed that sump pump removal would produce a quantifiable decrease in inflow (McCormack et al. 2000). Rehabilitation of two basins in the City of Olympia, Washington allowed direct comparison of the effectiveness of rehabilitation of the upper lateral versus the public sewer and lower laterals in order to reduce I/I, as well as the total removal that can be achieved when the entire system is rehabilitated (Merrill et al. 2000b). Trenchless technologies are often used for I/I control in sewers because they can be implemented with less traffic control, minimum conflict with other utilities, increased workers and community safety, and minimum dust and noise generation (Garcia-Marquez et al. 2000). The City of North Miami Beach, Florida initiated a system-wide I/I reduction program and selected formed-in-place liner installation for rehabilitation of damaged gravity mains. Through 1999, the City has installed 27,500 feet of liner, and a nearly 48 percent reduction in average daily flow has been seen to date (Rothman and Heijn 2000).

Public education.

Public involvement and education play a role in WWF control programs. Barger (2000) reviewed Little Rock (Arkansas) Wastewater Utility's Captain Sewer Water Conservation Education Program. The program has focused on water conservation and Captain Sewer now visits at least twenty-four schools each year and has appeared in 24 states and two foreign countries. A campaign to involve the public in developing a control plan for CSOs in Edmonton (Alberta, Canada) has evolved into a significantly broader program. "Towards a Cleaner River" has raised public awareness of the condition of the North Saskatchewan River, the functioning of the drainage and sewerage systems, and how people can help improve the river's water quality (Barth et al. 2000a). The Project Working Committee, the City and their consultant team developed a long term CSO Control Strategy to mitigate the environmental impacts of Edmonton's combined sewer system (Barth et al. 2000b). To address the problems facing Pogues Run and the West Fork River (Indianapolis, Indiana) from 23 CSO outfalls, a multi-million dollar comprehensive plan was formulated. Due to the multiobjective nature of the project and its funding needs, many agencies and neighborhood groups were involved to help resolve issues such as short-term funding, handling special waste, compensatory wetland creation, allowance for dam overtopping, and even the project's name and purpose (Kirk and Beik 2000).

Tunnels and interceptors.

Other research investigated various aspects of sanitary sewer systems that impact SSO and CSO control efforts. Spurred by the increased scrutiny by EPA and other regulatory agencies on SSO prevention, Jones and Schneider (2000) reviewed the elements that compose a pumping station design, including the results of client-consultant interaction that has resulted in exceptional reliability and reduced operational costs. The Western Carolina Regional Sewer Authority is completing construction of the largest sewer project in South Carolina to reduce SSOs and to protect water quality - 10 miles of deep trunk sewer up to 96 inches in diameter, located 20 to 45 feet deep along the fully developed Reedy River valley

(Hildebrand et al. 2000). The North Central Sewer Separation Project will separate storm water and wastewater pipes in a section of downtown Columbus, Ohio, USA (Keefer and Chase 2000). The Milwaukee Metropolitan Sewerage District authorized an emergency project to design and construct a new CSO pump station using a fast-track approach, as discussed by Maurer and Bush (2000). This discussion reviewed the use of large submersible pumps for CSO service, design considerations, procurement methods, and the challenges of fast-track design and construction.

The Vortex Drop Structure has been shown to be an effective energy dissipater and aerator. It is designed to dissipate the flow energy and aerate the wastewater, preventing emission of odorous gases, oxidizing the hydrogen sulfides, and protecting the drop structure from corrosion and abrasive wear. The analysis of multiple wastewater samples taken simultaneously upstream and downstream of the Vortex Drop Structures shows a significant decrease of dissolved hydrogen sulfides and a sharp rise in the dissolved oxygen concentrations downstream of the structures (Moeller 2000). Private pump stations (commercial, industrial, institutional, etc.) typically have been constructed as an immediate fix when no nearby wastewater facilities exist or to overcome sewer elevation differences. However, in many cases, insufficient documentation and coordination between the developer, engineer, permitting agency, and sewer system operator has rendered this component of the collection system seemingly non-existent (Huerkamp et al. 2000). Street storage refers to the temporarily storing stormwater in urban areas on the surface (off-street and on-street) and, as needed, below the surface close to the source. A case study approach, based on two largely implemented street storage systems, was used to explain the concept of construction and operation of street storage systems (Walesh 2000). Huisman et al. (2000) studied the propagation of surface waves on the operation of a urine separation system. The authors showed that the wave phenomenon had no adverse effects on the utility of the urine separation system, but could lead to the release of undiluted wastewater during a rain event.

Tunneling and interceptors play a role in WWF. The Columbia Slough Consolidation Conduit tunnel was a key element in alleviating CSO in Portland, Oregon. Rippe et al. (1999) described the design and construction of this soft ground tunnel project, with shallow ground cover and close proximity to an existing old concrete sewer, as well as the means of sharing risks between the owner and the contractor. Lannon and Roll (1999) described a challenging investigation of a deep tunnel interceptor blockage near the City of Niagara Falls (New York) that created persistent interceptor surcharging, prolonged upstream wet weather overflow following precipitation events, and an air release effect which propels wastewater over 27 meters (90 feet) upward from the interceptor through a drill hole during heavy rains. Roll (1999) described the diagnosis and restoration of diminished force main capacity in a wastewater transmission line linking the City of Niagara Falls, New York WWTTP with its largest pumping station. The flow limitation reduced first flush capture from the combined collection system and occasionally resulted in manhole surcharging up to street level. Westoll (1999) described sewerage and sewage-treatment projects intended to control combined-sewer overflows that cause nuisance during rainfall in the town of Driffield (Yorkshire, England). The projects include a new interceptor, constructed using trenchless technology, and a four-basin cyclic activated-sludge plant.

Litter, floatables, and settled solids.

Sewer solids which are deposited in combined and sanitary sewers during dry weather make up a significant component of CSO and SSO pollution. Detailed research investigating all aspects of solids in sewer systems has been underway in Europe for nearly two decades. Recent research has characterized the nature of the solids getting into sewer systems, how they behave in terms of transport, and some of the main aspects of their effects. Ashley et al. (2000) has demonstrated that in a number of catchments, the majority of pollutants found in suspension during storms, and likely to be discharged from overflows, originate from the predominantly organic 'near bed solids' which accumulate in systems during dry weather. This knowledge has been used to improve the modeling of sewer solids behavior. The USEPA has also investigated the causes of sewer solids deposition and the development/evaluation of control methods to prevent sediment accumulation. Control of sewer sediment not only protects urban receiving water quality but also protects sewer structural integrity (Fan et al. 2000b). Chen and Leung (2000) demonstrated that the sediment phase played a key role in oxygen utilization in a sanitary gravity sewer. Their study indicated that the sediment phase contained more active biomass than the sewage phase. Del Giudice et al. (2000) examined supercritical flow in a bend manhole used in sanitary sewers, and introduced the bend cover, which allows air entrainment into the downstream sewer. The bend cover may significantly increase the performance and capacity of bend flow and may easily be added to existing manholes. A three-dimensional particle settling model was used to predict the benthic exposure zone to sewage solids for a large marine outfall and diffuser serving Nanaimo, Canada. The predicted exposure zone was determined largely by horizontal advection, and to a lesser extent by the relative amounts of floc and non-floc solids settling at two different rates (Hodgins et al. 2000).

Riverine litter and floatables occupy a spatial and temporal position in any systematic analysis of river systems and

represent a problem that was increasing in scale. Quantifiable source factors of litter in the river Taff, South Wales, United Kingdom, system were found to be mainly sewage inputs through CSO and fly tipping. Sewage-derived material constituted approximately 23% of all items on the river, large quantities of waste, especially plastic sheeting, originated from fly tipping sites (Williams and Simmons, 1999). Burgess et al. (1999) reported that the City of Indianapolis developed five CSO control facilities as "pilot" facilities, for the purpose of establishing and demonstrating the local suitability and effectiveness of the various technologies that they employ. Preliminary results, with emphasis on the capture characteristics of the floatable debris netting trap facilities, were presented. Bridgeport's (Connecticut) Water Pollution Control Authority has recently faced the problem of floating debris and the sound's high tide. These drainage problems have been successfully solved by building new flow-control regulators with integrated automatic radio (wireless) and telephone-modem (wired) control, water-flow, and instrumentation technologies (Morrill and Sound, 1999).

Arthur and Ashley (1998) examined near-bed solids transport in combined sewers, developed a method to estimate the rate of sediment transport near the bed in sewers and concluded that near-bed transport of sediment may contribute to the first flush phenomenon in sewers. A study to quantify the first flush phenomenon in stormwater runoff failed to identify any consistent, strong indication that the first flush runoff from a storm contains higher concentrations of pollutants than the event average. Analysis of SS in the River Seine (Paris, Fr.) both upstream and downstream of major CSO showed that SS from wet-weather events settled rapidly, after which they are gradually mobilized from the river bed during dry weather (Estèbe et al., 1998). Dimensionless mass versus volume curves for 197 runoff events in 12 separate and combined sewer systems depended on the pollutant, the site, the rainfall event and the workings of the sewer system. No general relationships were established because of the complexity of the phenomena involved and the multiplicity of influencing factors (Bertrand-Krajewski et al., 1998). Only slight first flush effects for SS and conductivity of storm runoff were observed at single road inlets for two catchments in Yug. and Swed. and no first flush effect was recorded for pH or temperature. After a year of study, conclusions were that the first flush, if strongly present at the end of a drainage system, is not generated by the first flush of pollution input and that regression curves are not very reliable for prediction of the first flush load of pollution input into drainage systems (Deletic, 1998).

Real-time control (RTC).

Real Time Control (RTC) of wastewater systems involves using automatically adjusting weirs, flow separators, and similar devices to divert flow to unfilled portions of the collection system before overflow occurs. One of the more frequently applied RTC techniques in combined sewer systems (CSS) is the activation of in-line storage capacities by positioning regulators such as moveable weirs and gates into the collectors. Campisano et al. (2000) presented the results of RTC application to the Roma Cecchignola CSS through the use of an advanced hydraulic model. Comparison of the results obtained with the tested strategies showed that a global control strategy reduced overflows considerably more than a local control strategy. Charron et al. (2000) presented the results of a study of RTC to reduce CSO in and around Louisville, Kentucky, which showed a global RTC strategy would enable a more efficient use of the existing system capacity and reduce the overall cost of the CSO control. Cigana (2000b) introduced the use of linear overflow devices to help municipal managers achieve increased retention of sewage in a sewer while protecting against flooding. Cigana's examples demonstrated that the required water head was reduced by 50% for the same overflow rate. Jain (2000) summarized the hydraulic characteristics of a two-ramp drop structure used for diverting flows from near-surface storm-sewer systems to underground storage tunnels. The construction of this structure may be more suitable in urban areas where an open-cut construction is not feasible. Lavallée et al. (2000) reviewed the RTC system installed for the Quebec Urban Community (QUC), Canada. The results showed that a Global Predictive Real Time Control (GP-RTC) strategy on the Westerly Sewer Network was successful in terms of proven efficiency. GP-RTC meant that only 4 storage facilities would be required instead of the 7 needed without GP-RTC, a 22% savings (Pleau et al. 2000). Pollution-based RTC, or PBRTC, is designed to reduce the potential pollutant load on receiving waters during wet weather without expansion of transport or storage capacity. In branched interceptor systems PBRTC reduced CSO pollutant loads by more than 20% compared to volume-based RTC (Risholt 2000). Stinson et al. (2000) presented results of two case studies of RTC on portions of sewerage systems near Paris, France and in Quebec City, Canada. Villeneuve et al. (2000) compared three RTC strategies used in a collection system in terms of optimization of the use of the system capacity and the cost of long-term CSO control. The Philadelphia Water Department used the SWMM EXTRAN and SewerCAT models investigate RTC in its Southwest Drainage District (Vitasovic et al. 2000). Schutze et al. (2000) reviewed RTC for an integrated system that included the collection system, the treatment plant and the river. The results of their work was the development of an algorithm for the complete urban wastewater system and the methodology for parameter optimization.

RTC of combined and sanitary sewer systems aims to reduce overflows by better utilizing the existing storage in a

systems using real-time data such as rainfall and water level data to control adjustable weirs or pumps. Gonzalez et al. (1999) worked on the development and simulation of RTC systems for urban or metropolitan drainage systems with CSO or flood problems. They reported some conclusions and encourage the use of RTC systems on sewer systems. In response to floods in 1982, the Urban Community of Bordeaux decided to make improvements in their stormwater management system. Studies indicated that CSO have a significant effect on the environment. Therefore, emphasis will be placed on improving the management of the sewer system during rains and on the design of new storage structures and new treatment plants (Briat et al., 1999).

Artina et al. (1999) presented an evaluation of the benefits given by different configurations of storage tanks in a virtual but likely urban pilot site. The study showed that RTC, even if always useful for the reduction of overflow volume and frequency, in some cases can increase the discharged loads, under the hypothesis of complete mixing without settling in tanks. Fuchs et al. (1999) described the results of a study of the potential of real-time control of CSO for the combined sewer system of the city of Dresden. The results showed a significant 5% to 90% (mean more than 35%) reduction of the overflow volumes and loads for the controlled state compared to the uncontrolled one.

To address the problem of optimal water distribution to a range of retention reservoirs in an urban sewer network during rainfall events, Marinaki et al. (1999) proposed a linear multivariable feedback regulator that was developed via a systematic design procedure, including a simplified model, a quadratic minimization criterion, and subsequent application of the linear-quadratic optimization method. Simulation tests for a particular large network and various inflow scenarios indicate that significant overflow reductions were achieved by the application of the linear-quadratic regulator. Pfister and Cassar (1999) described measurement and modeling techniques developed for using X-band radar estimates of precipitation for RTC in a combined sewer system.

Villeneuve et al. (1999) presented a study of three types of RTC alternatives and conventional static control, applied to the Western section of the Quebec (Canada) Urban Community (QUC) sewer system. At the end of the long term CSO control plan it was projected that the QUC will control more than 85% of the CSO, for a total cost of US \$107,000,000 which was 37% less than what had been estimated before the introduction of RTC. Risholt et al. (1999) reported on a project to document current discharges of pollutants and to find potential reduction by implementing RTC of the wastewater system in Fredrikstad, Norway.

Offline simulations carried out with a variety of control conditions suggest that great benefits were to be expected using global control with precise forecast information compared to a static system with local control only. Quirnbach et al. (1999) presented an approach to joint operation of an urban drainage system and the corresponding sewage treatment plant. This operation was based on real-time flood forecasts, which were computed with the aid of radar rainfall measurements to minimize the combined negative effects of the hydraulic load (water quantity) and the pollution load (water quality) in the receiving waters during floods. Schmitt et al. (1999a) developed a new management strategy of the City of Nancy's sewage system (Lorraine, France) in order to reduce rainwater pollution overflows using a model which simulated flows in interceptors, transport of dissolved and solid pollutants, and precipitation, flocculation and sedimentation in WWTP. This new management strategy, optimizing the use of existing infrastructures, aims to conciliate flood risk management and the reduction of pollution overflows into the Meurthe River (France). Soeda et al. (1999) presented a case study of proposed improvements to combined sewer systems with no construction of new facilities and effective utilization of existing facilities through various modifications of stormwater pump operations. This system proved an effective means of reducing overflows and reducing pollutant loads from combined sewer systems.

Weib and Brombach (1999) examined the application, advantages, and hydraulic performance of devices for water level control like movable weirs (self-regulating or auxiliary powered) or siphons which were frequently used at overflow structures in urban drainage. Special focus was given to possible critical points and limits of application. Yagi and Sheba (1999) applied fuzzy logic control and genetic algorithms to achieve improved pump operations in a combined sewer pumping station. It was found that current pump operations can be improved by adding the sewer water quality to the input variables and to the fitness function; the improved operations can reduce not only floods in the drainage area but also pollutant loads discharged to the receiving waters.

CSO storage tanks and structures.

Temporary storage at CSO and SSO outfalls, with effluent returned to the system for treatment when system loading subsides, was a widely practiced method of WWF control. Some authors focused on modeling and design of storage structures. Harwood and Saul (1999) described how the computational fluid dynamics software Fluent was used to

simulate the hydraulic and particle retention efficiency performance of three extended stilling pond CSO chambers in the United Kingdom. It was concluded that where the effective retention of neutrally buoyant particles was a design criterion, increasing the size of the chamber may not be the most appropriate solution. Hobbs et al. (1999) discussed the use of flow equalization basins (FEB) for control of SSO and CSO. FEB increases systems capacity dramatically by retaining excessive flows until the collection system was better able to handle them and cost considerably less than more traditional methods. Maglionico (1999) proposes a methodology for the design of CSO tanks aimed to control first foul flush in sewer networks, based on a five years period of field continuous measurements carried out on rainfall, discharge and water quality in an experimental catchment near Bologna (Italy). Stovin et al. (1999) compared the results of simulated flow patterns and gross solids separation predictions with field measurements made in a full size storage chamber within an urban drainage system. Although estimates of total efficiency based on the observed settling velocity distribution differed from the measured values by an average of $\pm 17\%$, the simulated efficiencies agreed with the field observations in identifying the most efficient configuration. Van Mameren (1999) presented a method of using the results of rain series calculations as a design tool for stormwater sedimentation tanks, and demonstrated the method with an example.

Other papers presented case studies of CSO and SSO storage. For a better understanding of the spill over into the receiving waters, recorded data from 90 CSO tanks with a collective monitoring time of more than 300 years were compiled and analyzed by Brombach et al. (1999). A ranking procedure was proposed for an easy to handle evaluation of the overflow activity of CSO tanks. Hartshorne and Cadman (1999) described the design and construction of a 12,500 m³ capacity stormwater storage tank in Westbourne Avenue, Rhyl (United Kingdom). The finished structure was completely buried and incorporates new pumping plant to pump dry-weather and storm flows. Kearney and Schoettle (1999) described methods of cleaning dewatered CSO-storage basins at the Spring Creek Auxiliary Water Pollution Control Plant, which was used for temporary storage and treatment of CSO in New York City. Murphy et al. (1999) report on an in-line CSO storage facility constructed of bolted together precast box culvert sections that was designed and built by local engineers and contractors in the City of Bangor, Maine. This inexpensive CSO storage option has numerous advantages over the alternatives. A cost-effectiveness analysis conducted by the City of Slidell, Louisiana demonstrated that an offline storage-facility would produce a substantial capital cost savings over multiple, decentralized line repair projects to achieve the same level of SSO control. The completed project applies commonly accepted technology to produce a system that worked within the funding constraints, was acceptable to the general public, and was easy to maintain for the operators (Prellup, 1999). Wada and Miura (1999) attempted to reduce CSO using a large-scale storage pipe, which was constructed for flood control. Using a movable diversion structure permitted use of the storage pipe for both flood control and CSO control.

The influence of the experimental procedure for separating a sample by settling-velocity fractions was demonstrated. This not only takes into account the settling-velocity characteristics of wastewater and stormwater SS but also considers SS which influence settling velocities, ultimately impacting the design and management of sewer networks (Lucas-Aiguier *et al.*, 1997). The settleable and nonsettleable SS concentrations were measured during a storm event at a combined WWTP in Sacramento, Calif. (Whalberg *et al.*, 1997). While influent settleable and nonsettleable SS concentrations varied throughout the storms, the primary-sedimentation tanks were 100% efficient in removing the settleable solids the tanks were designed to remove.

CSO treatment.

Another approach to CSO and SSO control was to treat the effluent before it enters a receiving water. One widely-used approach to CSO and SSO control is to improve the ability of wastewater treatment plants (WWTP) to adequately treat high volume wet weather flows. The Binghamton-Johnson City Joint Sewage Treatment Plant, New York, is expanding its wastewater treatment facilities for three purposes: (1) to meet effluent limits for discharge to the Susquehanna River; (2) to increase the primary treatment capacity to treat peak storm weather flows up to 60 MGD; and (3) to increase the secondary treatment capacity to a minimum of 35 MGD. Aridgides et al. (2000) conducted a pilot-scale evaluation of biological filters that would fit within the existing site limits and allow elimination of the peak wet weather bypassing. In order to minimize CSOs to local receiving waters, the Philadelphia Water Department began a program to maximize flow treated by the existing WWTPs during periods of wet weather. As part of this effort, Ferguson et al. (2000) documented the effect of variations in influent characteristics, operational procedures, and minor physical modifications on clarifier performance. In the City of Edmonton, Alberta, Canada's CSO Strategy, a preferred method of control was to convey more flow to the WWTP for treatment and expand treatment capacity. In order to understand and evaluate the hydraulic relationship between the upstream collection system and the WWTP, a detailed hydraulic model was developed as part of the collection system hydraulic model (Gray et al. 2000).

Kurtz et al. (2000) presented the results of pilot testing of high rate physical chemical treatment technologies in a New York City WWTP. All units performed well when operating correctly, removing between 69% and 84% of TSS on average. King County, Washington modified their continuously- operated Alki Treatment Plant to an intermittently-operated wet weather facility, and they successfully demonstrated that treatment of wet weather flows was possible after modifications to the existing primary treatment facilities (Maday et al. 2000). An analysis by Moffa et al. (2000) demonstrated that retrofitting existing wet-weather flow facilities was technically feasible in most cases (a function of site-specific conditions and treatment requirements) and may be more cost effective than construction of new conventional control and treatment facilities. A related paper by O'Connor and Goebel (2000) indicated that retrofitting processes better enabled communities to meet the U.S. EPA's National CSO Policy and stormwater permitting program requirements. The Arlington County (Virginia) WWTP underwent a retrofit to meet a proposed mandatory ammonia and voluntary total nitrogen standard and to reduce wet-weather plant bypasses. The main components of the wet weather management plan were the new flow equalization basin, the operational flexibility in terms of the feed to the individual aeration tank passes, the flexible aerobic/anoxic swing zones and the retrofitting of the secondary clarifiers (Pitt et al. 2000c). Camp Dresser & McKee Inc. used microsand-ballasted high-rate clarification in WWF treatment for a wastewater collection and treatment system (Vick 2000). Chemically enhanced high rate separation has been shown to offer a robust treatment alternative for CSO, SSO and excess WWF at WWTPs, and will be evaluated by USEPA's ETV Program (Zukovs et al. 2000).

Hufnagel et al. (1999) reported on the collection and analysis of data from six CSO demonstration facilities in the Rouge River watershed (Michigan) from June 1997 through September 1998, and discuss performance, operational experience, and insight gained on design of facilities from an operational perspective. Andoh et al. (1999) presented the results of testing of a novel self-cleaning CSO device at the United Kingdom National CSO Test Facility at Hoscarr WWTP, Wigan, and concluded that CSO screening systems offering 4 mm two directional screening standard were significantly more efficient than 6 mm screens and might not entail any additional cost. Averill et al. (1999) described pilot-scale process development and full-scale demonstration work, and discussed considerations for the implementation of a high-rate physical-chemical treatment process that has been developed for use in satellite treatment systems to control CSO in Ontario, Canada.

The HydroSwitch consists of a control structure on a storm sewer, a diverting pipe to a receptor sewer system, a special slow control gate enclosed within a baffled inner compartment and a hinged boom trap to collect floatables. An installation in the District of Karlsruhe, Ger. removed 48% of SS and 32% of COD (Pisano, 1998). The Hiawatha CSO regional Treatment Facility in Syracuse, N.Y. demonstrated and tested vortex and storage abatement strategies with high-rate disinfection. The estimated construction cost for the 1.84 m³/s (65 ft³/s) CSO facility is \$3.5 million or about \$1.9 million/m³-s (\$50 000/ft³/s) (Miller et al., 1998). A pilot-scale study for CSO treatment was conducted in Toronto, Ont., Can. with a CSO which had highly variable SS that settled poorly. Polymer coagulants improved solid/liquid separation efficiency and provided an effluent suspension amenable to ultraviolet (UV) disinfection (Averill and Cairns, 1998).

The NORSD operates three WPCP capable of handling 5.167 million m³/d (1 365 MGD) of WWF (Debevec, 1998). An extensive flow monitoring and sampling study, including analysis of the influent and effluent BOD, SS, bacteria, NH₃, and seven metals at the NORSD's Westerly CSO Treatment Facility indicated improvements are needed for inlet hydraulic conditions and peak design loading rates should be reduced (McMasters et al., 1998).

Field and O'Connor (1997a) presented a strategy for the abatement of pollution from storm-generated SSO by maximizing flow to the WWTP, maximizing treatment capacity, and using CSO-control technology methods in addition to inflow reduction, cost-effective-sewer rehabilitation, and sewer-system inspection and associated cleanout and repair. Field and O'Connor (1997b) described a strategy to optimize CSO-control systems maximizing the use of existing system before new construction and sizing the storage volume in concert with the WWTP capacity to obtain the lowest-cost storage-treatment system.

The Actiflo[®] method is a compact physical-chemical water- treatment system that is being used increasingly for treating wastewater and CSO. The method uses weighted settling combined with lamella settling and typical efficiencies are: SS- 85%, COD-60%, TKN-18%, total P-85% and also removes heavy metals efficiently (Plum *et al.*, 1997). An urban stormwater-treatment system has been designed in order to obtain treated effluent satisfactory for bathing. This process combines air flotation, sand filtration, and UV disinfection (Laine *et al.*, 1997). An alternative BMP, bioretention system was proposed and consists of a rock berm and alternating strips of native grasses and stiff grass hedges for control of stormwater quality in Austin, Tex. (Murfee *et al.*, 1997). Treatment of urban-stormwater runoff was studied using a field-

scale submerged aerobic-biological filter (SABF) system. The study showed that a SABF system may be suitable for stormwater treatment (Anderson *et al.*, 1997).

Field *et al.* (1997b) discussed the application of swirl and vortex separators for the control of pollution from CSO and stormwater discharge. Design, application, and performance were presented for the U.S. EPA swirl concentrator, Storm King[®], and Fluidstep[™] technologies. Smith and Andoh (1997) discussed a new generation of hydrodynamic separators with an integral self-cleaning-screening system termed the Hydro Swirl-Cleanse[™]. This system ensures the removal of all material larger than a specified aperture size, e.g., 4 mm — 6 mm. A scaling protocol describing the residence-time characteristics of hydrodynamic separators, was discussed in terms of its importance for the removal of pollution from wastewater (Tyack and Fenner, 1997). A study evaluated various CSO-treatment technologies, e.g., vortex separator, circular clarifier, horizontal-flow- plate clarifier, and an inclined-rotary-drum screen and indicated that the vortex separator and plate clarifier are capable of 50% SS removal and 30% BOD removal (Schmidt *et al.*, 1997).

Daligault *et al.* (1999) reported on two settling devices treating rainwater from urban drainage areas and equipped with secondary sludge treatment, which were monitored over a period exceeding one year. From analyses of the settled or extracted sludge it was possible to characterize the pollutants retained in the lamella settlers. To estimate the effect of enhancing settling in CSO storage basins by flocculation, a free growth and break-up model was developed and implemented by de Cock *et al.* (1999). Del Giudice and Hager (1999) discussed design and performance parameters for sewer sideweirs, which in a combined sewer system were used for diversion of excess discharge during rainfalls. Also discussed was the throttling pipe, which was a simple device to limit the discharge to treatment facilities. Dormoy *et al.* (1999) reported the results of a simulation of a WWTP with activated sludge, and concluded that it was advisable to allow for increased sludge production, O₂ requirements and also sludge quality (fermentability) when stormwater was treated. Faram and Andoh (1999) described the results of a program of numerical studies that were undertaken in order to assess and optimize the fluid-dynamic performance of a novel non-powered self-cleansing CSO screening system, the Hydro-Jet Screen[™]. Observations of the operation of both model and prototype scale units have indicated good qualitative correspondence with the predictions in terms of overall flow patterns, and have confirmed the superiority of the recommended design in terms of its self-flushing capabilities.

Green *et al.* (1999) examined the performance of constructed reed beds from a WWTP with storm treatment reed beds and another site with a combined storm and tertiary treatment reed bed. The results illustrated that sites with combined storm and tertiary treatment reed beds experienced a level of performance matching that of sites with tertiary treatment systems, with averages of 2.2 mg/L BOD₅, 3.0 mg/L TSS, 1.25 mg/L NH₄-N and 12.2 mg/L TON. Luyckx *et al.* (1999) compared the separating efficiency of an improved high-side weir overflow and a hydrodynamic Storm King[™] separator. They show that when higher removal efficiencies were wanted, the hydrodynamic separator can technically as well as economically compete with simpler structures. The District of Columbia CSO Abatement Program included construction of a 400-MGD swirl concentrator at the outfall of the District's Northeast Boundary combined sewer; an outfall responsible for approximately 50% of the total CSO from the District. Extensive pre- and post-construction monitoring of instream DO concentrations up and down stream of the outfall indicate that the separator has had a dramatic impact on DO concentrations downstream of the outfall; cumulative frequency analyses indicate virtually no difference in DO concentrations between the upstream and downstream meters since the swirl concentrator went online (Murphy *et al.*, 1999). The problems created by sediment deposits in combined sewer systems (sanitary and storm) include a loss in conveyance due to these deposits which contributes to hydraulic overloading, leading to flooding, premature operation of CSO, and the washout of sediments through CSO into urban watercourses during times of storm. Skipworth *et al.* (1999) described an experimental laboratory investigation of the erosion and subsequent suspended sediment transport of an in-pipe, fine-grained, organic, cohesive-like sediment deposit analogous to those found in sewers. Vaes and Barlamont (1999a) discussed the implications of new design and analysis techniques and combinations of new and older components in combined sewer systems based on an evaluation of the various approaches and technologies used over the last eight years in Flanders, Belgium.

Schindewolf *et al.* (1997) reported on the construction of Houston, Tex.'s wet-weather-control facilities. The 1.2-billion dollar project includes unique wet-weather facilities that have storage, treatment, and discharge functions. Stirrup *et al.* (1997) of Hamilton-Wentworth, Ont., Can. plan to reduce pollution caused by CSO into Hamilton Harbor through construction of several offline detention-storage facilities and the implementation of a RTC system. Sherrill *et al.* (1997) presented the methodologies and results of the rating of the Detroit, Mich. collection system to both transport and store combined, which are general enough to have widespread application throughout the CSO community. The optimization of the insystem storage within the collection system, including the impact of maintenance considerations is also discussed.

Portland, Oreg. began an extensive CSO program in order to meet requirements of the Oregon Department of Environmental Quality regarding the reduction of CSO. A new pipeline will convey wet-weather CSO to the City's 300 mgd WWTP to store flows exceeding the treatment capacity during the peak wet-weather event (Williams *et al.*, 1997). The process and monitoring for bypassing during storm events was found to be inadequate at a small WWTP in Ontario, Can. Modifications were made to the bypass lines and to other areas of the plant and the staff was trained on these modifications. Consequently, BOD loadings were reduced by 89%, SS loadings by 83% and NH₃ loadings by 93% (Hegg *et al.*, 1997).

A CSO with a perforated screen (6mm aperture), which prevents passage of large solids, was evaluated at a WWTP with flows up to 180 L/s. Both raw and treated wastewater were used to simulate CSO at different strengths and the system was found to operate satisfactorily with no moving components (Jeffries *et al.*, 1997). Wong (1997) described the fundamental mechanism behind continuous deflective separation (CDS) technology and outlined the potential application of the technology for pollution abatement in stormwater systems and other WWF applications.

Field and O'Connor (1996a and 1996b) discussed the design, evaluation, and application practice enhancements for swirl and vortex technologies in their dual use for flow regulation and reduction of settleable solids, as part of a CSO- and stormwater-pollution-control system. Wong *et al.* (1996) described development of an innovative solids filtration system from stormwater, which shows advantages over traditional gross pollutant traps and over some vortex separators as well. By utilizing the circular flow action, this system prevents the filtration screen from blockage and, unlike vortex separators, maintains its effectiveness with increasing flowrates. The system is based on a continuous deflective separation (CDS) mechanism developed by Pollutec Ltd. (now CDS, Inc.). Application of this technology can be also extended to CSO management. Advantages of a plate settler versus a conventional settling tank for management of CSO in Osaka City, Japan, were evaluated by Takayanagi *et al.* (1996). The plate settler achieved desired removal of SS at influent quality fluctuations, was easy to maintain, and required one-third of space required for a conventional settling tank.

A pilot study conducted by Columbus Water Works using the Storm King vortex separator projected annual SS reductions of 80% and COD of 70% at a hydraulic loading of 0.23 m³/m²/min (5.7 gal/ft²/min). At higher hydraulic loading of 0.73 m³/m²/min (18 gal/ft²/min) SS reductions of 50% were observed (Water Eng. & Mgmt., 1996).

Based on pilot test results, Briat and Delporte (1996) discussed the Densadeg lamellar separator from the Degremont Company for treatment of WWF. The Densadeg separator accomplishes optimized flocculation with the contact mass and effective lamellar settling. It is compact, flexible, and efficient and can be used either alone or in connection with a storage basin.

Averill *et al.* (1996) discussed interim results of a Canadian multi-agency initiative to test technologies for the treatment of CSO under realistic field conditions. A modular, automated pilot plant, composed of an elevated tank, interchangeable CSO treatment technologies, and a conventional clarifier, is located in the City of Scarborough, near Toronto, ON, Canada. The Storm King[®], a vortex separator, has been the first CSO technology tested and has shown promising results to date. The data collected in this study will add to the knowledge of vortex field performance that is otherwise limited but necessary for a design of a full-scale facility.

Pfister (1996) discussed a laboratory study on the use of Fenton's Reagent, which is hydrogen peroxide coupled with divalent iron salts, for treatment of CSO in existing overflow tanks. Addition of the Fenton's Reagent to the CSO tank combines physico-chemical processes with chemical oxidation and can reduce COD by 30-50% and the bacterial content as well. Studies with real CSO are planned.

Herviou *et al.* (1996) presented results of a pilot-plant study with dissolved-air flotation for treatment of stormwater runoff. Dissolved-air flotation was shown to be effective for removal of SS, COD, and total hydrocarbons. This technology seems to be particularly suitable for hydrocarbon-contaminated stormwater. Also, this technology tolerates variations in the pollutant concentrations in the influent and can be used as a component of a treatment train (air flotation + filtration + UV disinfection) for the complete treatment of stormwater.

Brombach and Pisano (1996) presented results of a four-year performance evaluation of a rotary-drum-sieve filter for removal of floatables from CSO. The sieve, activated during storm events, treats the overflow of a CSO tank that serves a community of 3,000 in Birkenfeld, Germany. In four years, the sieve treated 97% of the overflow, which was 110,000 m³

of CSO, and removed gross solids effectively. Sieve maintenance was also discussed.

The use of magnetite assisted sedimentation and high-rate filtration, which combine the advantages of chemical coagulation with high-rate separation of flocculated solids, for treatment of storm-induced-sewer overflows was discussed by Booker *et al.* (1996).

Field and O'Connor (1996c and 1996d) presented an overview of SSO control as part of the EPA WWF research program. It was concluded that CSO technology should be considered for SSO control in addition to inflow reduction, cost-effective sewer rehabilitation, and sewer-system inspection and associated cleanout and repair.

Pujol *et al.* (1996) presented test results conducted in the Summer of 1995 on the Biofor[®] prototype (from Degremont) at the Acheres wastewater treatment plant of the Paris, France, metropolitan area. The prototype, an upflow biofiltration facility with heavy granular material, showed ability to treat high ammonia loading rates at high water velocities and to accept wet-weather conditions while maintaining good WWF performance. This process can be used in plants that accept periodic WWF.

Disinfection. Disinfection of CSO and SSO was practiced in many places. Disinfection of overflows is used to attempt to minimize the human health risks of CSO and SSO. The New York City Department of Environmental Protection performed a pilot study to evaluate the acute toxicity of CSO treated via ultraviolet irradiation (UV), chlorination/dechlorination, and chlorine dioxide. Toxicity effects observed in the treated effluents were associated with the untreated wastewater rather than the disinfection processes. Poor correlation was seen between field Microtox analyses and the off-site laboratory WET analyses (Santos *et al.* 2000). The Uptown Park CSO facility in Columbus, Georgia is the home of a national demonstration program for technology testing with peer review by a team of experts coordinated by the Water Environment Research Foundation (WERF). Four disinfection technologies have been examined in full-scale side-by-side comparisons to evaluate performance and operation criteria under similar CSO quality conditions. Vortex separators were used as contact chambers for three types of chemical disinfection, including sodium hypochlorite (with and without sodium bisulfite dechlorination), chlorine dioxide and peracetic acid. A compressed media filter followed by UV disinfection was also evaluated at various vortex pre-treatment levels in order to provide high quality control for the more frequent, more concentrated events. Turner *et al.* (2000) described methods for quantifying the statistical distribution loading on the receiving waters for a given solids removal and disinfection control scheme, and for operation of disinfection process control.

Wojtenko and Stinson (2000) provided a state-of-the-art review of the performance and effectiveness of ultraviolet (UV) light disinfection for CSO applications, and concluded that UV irradiation has potential for use in high-rate processes. As part of the expansion of 100-MGD WWTP in Wayne County, Michigan, a UV disinfection system design was provided - the largest of its type in the US. The UV system was designed to disinfect (measured using fecal coliforms) the "blended flow" from the primary and secondary treatment processes, and would be expected to provide disinfection that meets permit requirements for wet weather flows up to 175 MGD (Christeson and Fath-Azam 2000). Safety concerns and more stringent regulations regarding gaseous chlorine use have forced reconsideration of disinfection practices, with UV seen as an attractive alternative. However, varying flows pose a challenge for UV systems. Faisst *et al.* (2000) reported on the implementation of UV disinfection at two coastal communities carried out in response to these challenges. Wojtenko *et al.* (2000) presented a state-of-the-art review of chlorine dioxide (ClO_2) for high-rate CSO disinfection. In general, ClO_2 appeared to be effective for high-rate disinfection and a suitable Cl_2 replacement. The New Orleans Sewerage and Water Board has attempted to control the odor and disinfection problems common to SSOs through the use of Nok-Out, a blend of oxidative chlorine compounds and non-charged amines. Since its inception, the use of this blend has effectively controlled both odor and disinfection problems (Austin *et al.* 2000). The City of Atlanta's four westside, high-rate CSO facilities used coarse and fine screening followed by sodium hypochlorite disinfection. Disinfection optimization studies found that the CSOs exhibit a first flush, that the water quality varies throughout an event and between events, and that the CSOs are currently contact-time limited during the first flush in regards to disinfection (Richards and Gurney 2000).

One concern with using the standard methods for measuring microbial indicator concentrations in sewage before and after disinfection is that they fail to measure particle-associated microorganisms, thus underestimating the total concentrations present. A related concern is that particles and other matter in the water interfere with a disinfectant's ability to contact and, therefore, inactivate microbes. EPA researchers presented the results of two projects which examine the effects of particle association on measurements of microbial indicator concentrations in CSOs, and determine the effectiveness of four treatment trains for CSO disinfection and the effects of removing solids on the disinfection effectiveness of

chlorination and ultraviolet (UV) light irradiation (Perdek and Borst 2000a and 2000b). The USEPA has begun advocating that beach managers monitor marine water quality at bathing beaches using enterococcus, rather than the present approach which is usually use of a coliform indicator. Rex (2000) explored the potential impacts of changing from the fecal coliform indicator to the enterococcus indicator in three areas: (1) monitoring disinfection of wastewater, including CSO; (2) monitoring receiving water quality for the relationship between fecal coliform and enterococcus; and (3) monitoring changes in receiving water over time as improvements in CSO infrastructure are made. The analyses suggest that there is a potential impact on the ability of CSO facilities and wastewater treatment plants to meet new water quality standards.

Stinson et al. (1999) discussed high-rate disinfection technologies for CSO, including ultraviolet light irradiation, ozone, chlorination/dechlorination, chlorine dioxide, peracetic acid, and high-voltage electron beam irradiation. Discussions of the technologies included commercial availability and extent of use, state-of-development when not commercial, and where available, performance data and cost of either full-scale or pilot-scale installation. Also discussed was utility of increased mixing in concert with any disinfection technology. In 1996, the Vallejo Sanitation and Flood Control District (California) replaced an outdated chlorine gas disinfection system with a state-of-the art medium pressure UV system, in combination with a liquid chemical system for use as backup during wet weather periods. Tekippe et al. (1999) reviewed VSFCDD's three-year operating history, and presented a summary of startup and post-startup problems and their resulting solutions.

Four pilot units representing three different technologies were investigated at the Hartford, Conn. WPCP to determine the disinfection ability of UV on secondary effluent, CSO flows and combined secondary and CSO flows. Based on technical, operational and cost comparison of the pilot study, the disinfection of the secondary effluent using UV radiation and sodium hypochlorite (NaOCl) for CSO was recommended (Amirhor and Roach, 1998). Four alternative disinfection technologies pilots (UV, ozone, chlorine dioxide and chlorination/dechlorination) were evaluated for the Spring Creek Auxiliary Wastewater Pollution Control Plant in NYC. All technologies provided three to four log bacterial reductions and chlorine dioxide and chlorination/dechlorination were determined to be the most cost-effective technologies for the facility (Smith et al., 1998). A full-scale CSO demonstration in Columbus, Ga. evaluated side-by-side treatment methods for removing wet-weather contaminants and disinfection by sodium hypochlorite, chlorine dioxide, peracetic acid, and medium pressure UV (Boner et al., 1998). Stinson et al. (1998) presented the applicability of four high-rate disinfection technologies for treating CSO and SSO including ozone, UV, chlorine dioxide and high-voltage electron beam irradiation.

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